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THE METALLOGRAPHY OF METEORIC IRON

BY
STUART H. PERRY

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The present work forms No. 184 of the *Bulletin* series.

Alexander Wetmore,
Assistant Secretary, Smithsonian Institution.

PREFACE

A systematic treatment of the metallography of meteoric iron was prompted by the author's experience in describing an iron meteorite by metallographic methods somewhat more than a decade ago. He was then unable to find that any new meteorite had been so described, and the literature bearing upon the subject was scanty. It consisted chiefly of the writings of iron and steel technicians in the books and periodicals of that trade and a few contributions in the proceedings of scientific bodies. The work done by such investigators upon meteoric iron being incidental to their studies of artificial iron and other metals, they naturally passed over many matters of interest to students of meteorites as such. Also, in their investigation of meteoric iron they did not utilize fully the methods of research that were in common use in the study of artificial metals.

The present work aims to apply metallography, both theoretically and practically, to the study of iron meteorites. To that end the author has attempted to give a sufficient outline of the metallography of artificial iron and its alloys to enable the reader to interpret meteoritic structures; the principal types and structural features are described and illustrated; methods of research are explained; and finally a somewhat comprehensive bibliography is presented.

The illustrations have been selected from about 1,300 photomicrographs, covering more than a hundred meteoric irons. All these may be consulted at the United States National Museum. The author also has deposited all the negative plates in the Museum, where prints from any of them may be obtained. They were made mostly by graduate students in the engineering department of the University of Michigan, skilled in photomicrography of artificial irons, who from time to time acted as assistants in the author's laboratory work. Especially noteworthy was the work of A. W. Herbenar, his assistant for 2 years, not only in producing a large part of the photographs but also in working out details in the technique of etching and in finding numerous features of interest in the specimens examined.

The author's grateful acknowledgments are due to Dr. W. F. Foshag, of the United States National Museum, and to his associate, E. P. Henderson, for many courtesies and the loan of numerous specimens; to Dr. F. H. Pough, of the American Museum of Natural History, Dr. H. W. Nichols, of the Field Museum of Natural History, Prof. Charles Palache, of Harvard University, and Dr. H. H. Nininger, of Denver, for the loan of specimens; to Dr. Robert F. Mehl, of the Carnegie Institute of Technology, who kindly read the manuscript and made valuable suggestions; and to Prof. Clair Upthegrove, of the University of Michigan, for the use of the facilities of the metallographic laboratory of the university.

Stuart H. Perry.

Adrian, Mich., December 1, 1942.

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THE METALLOGRAPHY OF METEORIC IRON

By Stuart H. Perry

I. INTRODUCTION

Historical.—Before metallographic methods were applied to the study of meteoric[1] iron an extensive literature had been built up by the work of a number of able scientists, dealing with their classification, their chemical composition, and such structural features as could be observed at moderate magnification in oblique light. The most famous of those investigators was Cohen, whose Meteoritenkunde summarized the knowledge upon that subject up to the year 1905.

Their researches, however, were limited by the imperfect methods then available; for the ordinary microscope at best could reveal only the coarser contrasts in structure. The invention of vertical illumination opened a field of research that not only laid a new foundation for metallurgy but also greatly extended our knowledge of meteoric iron.

Vertical illumination was invented perhaps as early as 1865, and the illuminator in substantially its present form was described in the 1883 edition of W. B. Carpenter's book "The Microscope." It was used for a number of years by Sorby, whose description of the microstructure of iron and steel (1887) was the most important early contribution to that subject.

Its application to the study of meteoric iron, however, was singularly tardy. Although Cohen (1894) cited Sorby's work, and several others dealing with the microstructure of metals, and (1903) mentioned Reichert's new "metal microscope," which he said made possible photomicrographs up to a magnification of 200 diameters, he apparently made no use of the device, and his works are silent on the finer microstructure of meteoric iron. It was not until 15 years later that Pfann (1917) and Berwerth (1918) published the first discussions of such structures with photomicrographs, the result of studies made with a Reichert microscope that had become available in Vienna. Even so, until in quite recent years, scientists continued to describe and discuss iron meteorites in the language of the older writers. Nevertheless, while metallography has opened up a new and rich domain, the earlier investigations were accurate and exhaustive and still form an indispensable basis for the study of meteoric iron.

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[1] The terms meteor and meteorite are clearly distinguished, the former being applied to the body while in flight, the latter to such portion of it as reaches the earth. Similarly, a distinction is drawn between the words meteoric and meteoritic. In this work the author uses the term meteoric iron because its composition and structure were established while the mass was a meteor. In a few instances the word meteoritic is used in referring specifically to meteorites, or to some structure that developed in a meteorite after its fall.

A great many of the older descriptions are now of little value beyond the fact that they give the history and general characteristics of specimens. Octahedrites were easily recognized and classified, but scant information could be given regarding hexahedrites, and as to ataxites none at all. A restudy of all irons not recently described would be of great interest and doubtless would reveal errors in classification.

As mentioned later, the technique of analysis has so greatly improved that many new analyses should be made, especially of irons whose structure makes the proportion of certain components important. In many cases the only published analyses are 50 to 100 years old, and many of these seem inconsistent with the structure of the irons.

Macroexamination; etching.—Visual investigation of the structure of metals is based upon the appearance of a polished surface, on which structural components of varying solubility become visible when treated with an etching reagent. Etching may be of the ordinary kind, termed macroetching, or metallographic (micro) etching.

For the former, which is used for museum specimens, the surface is given a reasonably good polish and then etched with a dilute acid until its macrostructure has been brought out as clearly as possible. In the class of irons known as octahedrites the Widmanstätten pattern is revealed, often strikingly. In certain other types, which may possess a wealth of microscopic details, a mat surface is produced with no visible structure. Even under the microscope the roughness of the etched surface makes fine details invisible.

With macroetching the larger structural features can be studied well with an ordinary microscope at low magnification in oblique light—such as the general character of the Widmanstätten structure, the presence of small particles, and the size and form of larger inclusions. The compilation of photographs of meteoric irons published by Brezina and Cohen (1887), made in this way at low or moderate magnification, was an invaluable contribution to science and is still useful. But with macroetching it is quite impossible to study such features as granulation, minute inclusions, details of Neumann lines, and eutectoid structures or to observe the very important effects of selective etching.

Microexamination.—For metallographic study the procedure and the results are quite different. The polish, instead of being only reasonably good, must be of the utmost refinement—so perfect that no imperfections are visible even under high magnification. The surface is then etched very lightly—so lightly that the appearance is little changed, if at all, to the eye—and examined under a microscope with a vertical illuminator.

The picture thus seen is strikingly revealing. There is none of the roughness that obscures the field with ordinary etching; it appears like a finely drawn and delicately shaded map, upon which minute details can be photographed at magnifications up to 3,000 diameters or more. As compared with the same field viewed with oblique illumination, the lights and shades of structure are reversed. The strong contrast between taenite lamellae and the darker kamacite bands, as seen in oblique light, disappears. The sheen of the kamacite also disappears, and it forms a bright clear background upon which such details as grain boundaries and minute inclusions are conspicuous. Strange and beautiful eutectoid structures appear, which are wholly invisible with the ordinary microscope.

The reversal of lights and shades is explained by the fact that under oblique illumination areas not attacked by the etchant remain smooth and reflect the light away from the objective, while areas roughened by etching reflect light upward through the objective, thus making the former appear dark and the latter light. With central illumination the unattacked areas reflect all the light upward and therefore appear bright, while roughened surfaces reflect it partly away from the axis of the objective and thus appear darker.

The revelation of a structure by etching and microexamination is extended by varying the degree of etching, or the reagent used, so as to bring out certain structures or to show differences in solubility or composition, and by selective etching with reagents that affect only certain components.

Whether etching leaves a given detail depressed or in relief can often be determined by focusing upon adjacent structures under high magnification. Giving the axial beam of light a slight obliquity (e.g., 15°) may produce effects of shading that help to determine details of structure.

The use of polarized light, spectroscopic analysis, and X-ray analysis is discussed in Chapter XVII.

Despite the advantages of central illumination, ordinary oblique light still has important uses. It can be employed at much lower magnification—such as 5 or 10 diameters—which is not practicable with central illumination and therefore is useful in a general survey of the surface to be studied. The brilliant oriented sheen in certain irons is seen only in oblique light, and the colors of certain inclusions are more distinct. Taenite lamellae and particles sometimes produce striking effects that can be observed only with macroetching and oblique illumination.

Chapter XVII outlines the technical methods employed in the metallographic study of meteoric irons.

II. GENERAL TYPES OF METEORIC IRON

The classification of meteorites by the older writers and their descriptive terminology have long been accepted; it is therefore necessary at the outset to summarize briefly the recognized types and the more familiar structural features.

Meteorites are of three classes—those composed of stone (aerolites); those composed of a mixture of stone and iron (siderolites); and those consisting wholly of metal (siderites). The present work treats only of siderites. It does not cover the structures of the iron found in meteorites of the transitional types between stones and irons, or in the metallic grains found in stony meteorites; though in such of these as were examined the metallic structures were found to be similar to those of siderites of similar composition.

Siderites are classified in three groups—hexahedrites, octahedrites, and ataxites.

Hexahedrites.—Hexahedrites (designated by the symbol H) are composed of a single structural component, kamacite,[2] and have a nickel content of less than 6 percent. The proportion of nickel is quite uniform at around 5.5 percent, although a few analyses have indicated a somewhat lower percentage. Cobalt apparently always is present, the combined percentage ranging from about 6 to 6.50 percent.

Kamacite is cubic in crystallization and often shows a distinct cubic cleavage on broken surfaces. It may be structurally homogeneous, when the iron is called a normal hexahedrite (H); or it may show irregularly rounded or polygonal grains, sometimes of large size, when it is called a granular or grained (often inaptly "brecciated") hexahedrite (Hb). See plate 1.

Hexahedrites generally show one or more systems of long, fine, parallel lines known as Neumann lines, which may be conspicuous on a lightly etched surface when the light falls at certain angles. These lines, however, are not an invariable characteristic; some hexahedrites do not show them, while they are abundant in octahedrites and are sometimes found in ataxites.

The metallic surface with ordinary etching shows no other structural features, although often there are inclusions of iron phosphide (schreibersite) or iron sulphide (troilite), which sometimes are of considerable size.

Octahedrites.—Octahedral irons are characterized by the Widmanstätten structure—a network of bands crossing one another in two, three, or four directions (pls. 2, 3). The bands are composed of kamacite, usually bordered by thin lamellae of an iron-nickel alloy rich in nickel, termed taenite. Filling the angular interstices of the network are areas called fields, which are composed of plessite—a more or less fine mixture of kamacite and taenite—which assume a great diversity of form and structure.

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[2] In the language of metallography kamacite is alpha nickel-iron, and taenite (presently to be mentioned) is nickel-rich gamma. The iron-nickel system is discussed at length in Chapters VIII and IX.

These three structural components—kamacite, taenite, and plessite—are often referred to in descriptions as the trias.

Octahedrites are classified according to the width of the kamacite bands as follows, the letters in parentheses being the commonly accepted symbols (abbreviations of German words) for the various types:

Coarsest (Ogg), bands 2.5 mm. or wider.
Coarse (Og), bands 1.5 to 2 mm. wide.
Medium (Om), bands 0.5 to 1 mm. wide.
Fine (Of), bands 0.2 to 0.4 mm. wide.
Finest (Off), bands narrower than 0.2 mm.

The nickel content of the coarsest and coarse octahedrites is roughly 6 to 8 percent; of medium octahedrites 7 to 9 percent; of fine and finest 8 to 13 percent. It is impossible to generalize more exactly, because analyses show variations from these averages, and many of the older analyses cannot be accepted as accurate.

The lines of demarcation between classes also are not always clear. Some of the coarsest are practically hexahedrites, while the finest graduate into nickel-rich ataxites.

Cleavage in octahedrites.—As has been noted, hexahedrites often have a well-marked cubic cleavage. Occasionally octahedrites appear to yield a definite octahedral cleavage. This, however, is not a true cleavage. It does not take place along the cleavage planes of the iron, which are cubic, but is a mechanical separation along the octahedrally oriented bands, which are bounded by taenite lamellae.

Such a separation is commonly due to infiltrating rust and may be seen near the surface of weathered specimens. In the unique case of Horse Creek (Chapter XI) there is a highly perfect cleavage due to the presence of brittle iron-nickel phosphide (schreibersite) along crystallographic planes that are not octahedral.

The Widmanstätten structure.—While hexahedrites are featureless with ordinary etching, except for Neumann lines and grain boundaries, octahedrites show the striking and beautiful Widmanstätten structure. This structure, which is discussed at greater length in Chapter XI, is due to the crystallization of the kamacite in thin plates along octahedral planes and to the segregation of taenite in lamellae between the plates. Owing to the lesser solubility of taenite in ordinary etching reagents, the two components are left in strong contrast, producing a pattern of gray bands separated by fine shining lines of taenite.

Though the pattern is octahedral, the term octahedrite is in a sense a misnomer, because the iron is actually cubic in crystallization. The pattern originated in a higher temperature range in which the kamacite bands developed on octahedral planes. As the mass cooled it entered a new phase with a different space lattice, in which the formation of bands on octahedral planes was impossible. The macrostructure produced in the higher range remained, however, the pattern thus being in effect a pseudomorph of a prior structure.

The form of the pattern depends upon the direction in which the section is made with reference to the Widmanstätten structure. If it happens to be parallel with an octahedral plane there will be three systems of bands forming equilateral triangles. If it is parallel with a cubic plane there will be two sets intersecting at right angles. If parallel with a dodecahedral plane there will be three sets, two making angles of 109° 28′ and another bisecting that angle. If made in any other direction four systems of bands at various angles will appear.

As a mass of meteoric iron is generally in effect a single crystal, when the structure is regularly developed the directions of the bands are parallel throughout the mass. Individual bands can often be traced for many inches without interruption. The structure, however, is often irregular and the bands are wavy, interrupted, and sometimes barely distinguishable.

The fineness of structure increases with the percentage of nickel. The greater the nickel content the more taenite and the less kamacite appear; therefore the bands grow narrower and the taenite lamellae thicker and more abundant. At the same time fields of plessite become larger and more numerous.

In the coarsest octahedrites taenite lamellae are barely observable, or entirely lacking, and plessite is typically scanty or absent. In medium octahedrites taenite lamellae are conspicuous and plessite fields are abundant. In the finest octahedrites the greater part of the surface examined is found to consist of a plessitic groundmass in which the narrow kamacite bands are often widely separated. Finally plessite prevails wholly, the kamacite becomes vestigial, and with a nickel content around 14 percent the structure becomes an ataxite.

Ataxites.—The third group of irons, termed ataxites, appear to the eye to be without structure and under the ordinary microscope show only a fine mat texture.

The name (from the Greek ἀταξία, disorder) was given to irons that showed neither cleavage, Neumann lines, nor Widmanstätten structure. Though high magnification with central illumination reveals a rich microstructure, very little was observed by the older investigators by the methods available to them. Indeed, as late as 1915, O. L. Farrington wrote: "Some show a fine-granular structure, but others even under the microscope exhibit no division into grains which can be detected. They are, therefore, except for accessory minerals, quite structureless."

Two subgroups were early recognized—nickel-poor and nickel-rich ataxites. In the former the nickel content is approximately that of hexahedrites; in the latter it commonly varies between about 12 and 20 percent, with a few showing much higher percentages.

Ataxites were classified by the older writers into numerous subgroups, including the Cape (symbol Dc), Shingle Springs (Dsh), Babb's Mill (Db), Linville (Dl), Nedagolla (Dn), Siratik (Ds), Primitiva (Dp), and Muchachos (Dm). These designations or symbols appear in many museum labels and catalogs. Such classification, however, was based upon superficial characteristics and has little meaning from the standpoint of metallography. In the writer's opinion only two classes need be recognized, nickel-poor and nickel-rich ataxites.

The peculiar fact that an ataxite may have either a very low or a very high nickel content is explained in later chapters.

Transitional forms.—A number of octahedrites with very low, or very high, nickel content are barely distinguishable as such, their structures being transitional respectively from those of hexahedrites and those of nickel-rich ataxites.

Several irons showing a very coarse and irregular pattern, the width of the bands (or grains) reaching an inch or more, have been generally classed as coarsest octahedrites. In some of these the author can see no tendency to octahedral orientation, the large grains being irregular in form and disposition. The nickel content of these irons is as low as that of some hexahedrites, and their microstructure is characteristically hexahedral.

On the other hand, in some high-nickel irons classed as finest octahedrites the structure is almost or quite ataxitic. An example is Cowra (Ni-Co 14.25 percent) in which there are no typical kamacite bands but only needles or spindles of kamacite in a dense ataxitic groundmass, the only connecting link with octahedrites being an octahedral orientation of the needles, a feature found also in ataxites.

In some cases the assignment of an iron to one or the other group is more or less arbitrary. This matter is further discussed in Chapter XI.

Proportions of types.—According to the latest available figures, by Watson (1941), the total number of meteorites of all types is 1,202. Of these, 438, or a little more than one-third, are siderites. Of the three types of siderites, octahedrites are by far the most numerous, comprising about 75 percent of the total. Hexahedrites and nickel-poor ataxites (the latter very few) comprise about 15 percent and nickel-rich ataxites about 10 percent.

Interpreting structures.—Such terms as bands, lines, and needles are inexact, as they merely describe the appearance of structural details as viewed in section.

The kamacite plates in an octahedrite produce an appearance of bands, which vary in width according to whether the section is normal to their planes or oblique. If the section happens to be made parallel with the plane of a kamacite plate, it might be cut flatwise, in which case it would appear as a triangular or quadrangular field.

True plessite fields do not usually represent cross sections of large interstitial masses of that constituent, but oftener sections of plate-like bodies. Except in the fine and finest octahedrites the interstices among the kamacite plates are similar to them in form—that is, they also are plates bounded by octahedral planes. Thus, on a polished surface the section of such a tabular mass of plessite may appear (1) as a large field, if cut parallel with its plane; (2) as a wider or narrower band, if cut transversely to its plane; or (3) as a triangle or rectangle, if cut across a corner of the tabular mass.

The foregoing observations apply to a Widmanstätten structure in which the bands are closely packed. When they become sparse and widely separated, as in fine and finest octahedrites, the interstices are larger, and the plessite instead of being in thin tabular form appears in relatively large masses bounded by the octahedral planes. In such cases the fields represent cross sections of such masses, and they would be large regardless of the direction of the section.

The larger fields of plessite in the finest octahedrites (e.g., Butler, Carlton, Laurens County) (pls. 12, 13, 15) often enclose areas of minute kamacite needles or spindles, which are not found in coarser octahedrites in which the bands are less widely spaced. These are not true needles but sections of small lamellae. The thicker, rounded particles, usually termed spindles, are probably sections of small so-called "swollen" plates. This may be inferred from the fact that sections often show many spindles of similar shape but few or no rounded kamacite areas that would represent cross sections of a true spindle form.

Long needles of schreibersite (pl. 52) are probably always cross-sections of very tenuous lamellae, and the same is true of the long threads of taenite often found in plessite fields. Very short minute lines of taenite or schreibersite might conceivably be true needles, but even they are more likely to be sections of flakes of the precipitated component.

Minute rounded dots of taenite (pl. 40, fig. 2) may be assumed to be sections of rounded particles, and the same is true of the minute rounded dots of schreibersite that abound in some irons.

The nature of all such apparent structural features is often made clear by repolishing a surface, the slight reduction of the surface causing marked changes in the appearance of the structures.

Very fine black particles may not readily be identified; for, whatever their composition may be, the strong attack of any solvent etching reagent (not a staining reagent) along the interface causes such a particle to appear as a black dot. Thus, even if they are taenite, which is not affected by ordinary light etching, they may appear black.

Unless an iron is known to be phosphorus-free, however, such black dots are most likely to be schreibersite; and that assumption is practically confirmed if they are sparse or absent in the vicinity of masses or large needles of that component (pls. 5, 54, 56, 59).

In irons showing a gamma-alpha transformation structure (Chapter XI) many minute black particles may appear with ordinary etching which are not phosphide. Their identification is discussed in Chapter XVII.

The plates afford many illustrations of the various structural appearances referred to and of the effects of different etchants.

Analyses.—The published analyses of meteoric irons cannot always be accepted as dependable. Even in apparently homogeneous hexahedrites and ataxites the composition may vary somewhat in different places, while in octahedrites the structure is so diversified that two samples taken from the same specimen may show marked differences.

It is often impossible to know whether the material used was a piece cut off or a sample of borings or sawings, which would give a fairer average of composition. Even borings or sawings may include part of a large hidden inclusion, which would cause the analysis to reflect an undue proportion of sulphur, phosphorus, or other ingredient. The difficulty in isolating kamacite, taenite, and plessite, and the impossibility of separating the nickel-poor taenite from the nickel-rich kind, have caused wide variations in the analyses of these components.

The methods used in determining nickel and separating it from cobalt were formerly less satisfactory than now; in fact, the older analysts often did not try to separate them, giving a combined percentage for the two. Recent analyses often show more cobalt and less nickel than older ones of the same irons. This, however, is of minor importance from the metallographic standpoint, as nickel and cobalt have virtually the same effects upon the transformation of meteoric nickel-iron.

The older analyses (many 75 to 100 years old) should be taken with reserve. Likewise, when an analysis, even though of recent and reputable origin, appears to be wholly inconsistent with the structure of the iron, it is justifiable to suspect some error or accidental factor in the determination of the composition. For example, if an analysis of a fine octahedrite showed only 5 percent of nickel, it obviously could not be accepted.

Errors in nickel content.—In some of the old analyses errors are conspicuous. For example, analyses made in 1866 and 1876 of Prambanan and Yanhuitlan, fine octahedrites, gave the impossibly low percentages of 2.86 and 1.85 nickel. Later analyses showed, respectively, 9.30 and 7.36. Different analyses of the same iron also show great variations; for example, analyses of three Coahuila irons regarded as identical gave nickel percentages of 2.10 to 7.42.

In many old analyses the nickel content was greatly understated. Thus, analyses of 25 irons (including many medium and fine octahedrites), of which only three were later than 1880 and most of them between 1840 and 1870, show very low percentages, mostly from about 2.5 to 3.5; but 15 of these irons analyzed later showed in only one case less than 6 percent and mostly 7 to 10 percent. Of 30 analyses of low-nickel irons (hexahedrites, coarse and coarsest octahedrites, and nickel-poor ataxites) made since Farrington's compilation (1907), not one shows less than 5.25 percent of nickel; and of 58 of the more recent analyses of all types of irons, only two show slightly less than 5 percent, of which one is clearly erroneous. We may therefore fairly conclude that there are very few irons, if any, with less than 5 percent of nickel.

At the other end of the series the nickel content in some of the finest octahedrites may have been overstated. Thus 14.82 percent of nickel (15.28 percent of nickel and cobalt) in Tazewell, as determined in 1855, seems clearly to be excessive, as the author knows of no other iron with so high a percentage that does not have a typical ataxite structure.

In this work analyses are continually referred to, and it is impractical to give all the dates and references. Where there are two or more analyses the one quoted is either the latest or the one deemed most probably reliable. The figures can never be accepted unreservedly unless the analysis is recent and was made by an analyst of known competency.

III. PRIMARY CONSTITUENTS OF METEORIC IRON

Kamacite.—The principal component of meteoric irons is kamacite (approximately iron 94 percent, nickel 6 percent). Metallographically it is alpha nickel-iron. It is iron-gray, magnetic, with hardness between 3 and 4 on the ordinary Mohrs scale, being easily scratched by a needle, such as a very mild steel. It etches quickly, being soluble in dilute acids.

In the literature of meteorites kamacite is commonly designated as granular, hatched, and spotted. The granular form, as the name indicates, shows a structure of minute polyhedral grains. Hatched kamacite, appearing only in octahedrites, is marked by a profusion of fine transverse or oblique lines, giving a band (with macroetching) somewhat the appearance of a file. This structure, formerly attributed to Neumann lines, is a product of phase transformation, which is explained in Chapter XI. Spotted kamacite (mottled or darkened might be more apt), showing shaded or darkened areas, is less often observed. Like the similar structure frequently found in taenite, it is a transformation product.

Composition of kamacite.—The most satisfactory analyses of kamacite have been made from hexahedrites, which consist wholly of that material. They show a rather uniform nickel content of around 5.5 percent, with a few slightly below 5 percent. Some analyses have been made of the kamacite in octahedrites which show nickel-cobalt percentages around 7. Such figures cannot be regarded as a reliable index of its composition because of the difficulty in obtaining samples that are free from taenite.

As will be explained in chapters IX and XIII, about 6 percent is the upper possible limit of the nickel content of kamacite. Below that percentage the nickel content is indefinite; but, as previously pointed out, very few recent analyses show less than 5 percent of nickel in any meteoric iron.

Oriented sheen.—A characteristic property of kamacite is a distinct, often brilliant, oriented sheen, which changes as the specimen is rotated. This appearance, which is conspicuous only with macroetching, is also observable in many hexahedrites; but it is most striking in octahedrites, various bands becoming bright or dark in changes of light.

A number of explanations have been offered for the sheen—that it is due to Neumann lines, or to polysynthetic twinning; Vogel's suggestion that (at least in some cases) it is due to oriented submicroscopic particles of schreibersite; and the older view of Tschermak that it is due to minute or submicroscopic etching pits, cubic in form and oriented.

The first explanation is clearly untenable. A profusion of Neumann lines in one direction in some hexahedrites may give somewhat of the effect of an oriented sheen; but hexahedrites exhibit such a sheen in the absence of Neumann lines, and the same is true of the sheen of kamacite plates in octahedrites. A sheen is also found in the grains of granular ataxites, in which there are no lines.

A somewhat more acceptable explanation is the formation of ultramicroscopic etching pits, cubic in their angles and oriented according to the cubic planes of the iron, thus causing light to be reflected more strongly in three directions corresponding with the axes of a cubic crystal, the whole mass being unigrain in character. The influence of such etching pits upon the sheen, however, is hypothetical. The characteristic angular etching pits observed in artificial iron and other metals are so difficult to produce in meteoric irons that the author has never observed them. In some cases etching pits were quickly produced, but they were shapeless.

Vogel (1927) attributed sheen to the presence of phosphorus, stating that it is strongest in phosphorus-rich irons and weak or absent in those containing little phosphorus, thus constituting an index of the phosphorus content. The author cannot concur in that view.

Effect of atomic planes.—It would seem a reasonable explanation that the sheen arises chiefly, if not wholly, from the influence of atomic planes revealed by the etching process. For example, if the etched surface were parallel with a set of such planes it would be uniformly attacked. But if the surface intersected the same planes obliquely, the differential attack of the etchant along the edges of the slightly overlapping planes might produce a surface comparable with that of overlapping clapboards, from which light would be reflected more strongly in one direction. Further etching might conceivably develop along such lines submicroscopic etching pits with cubic orientation. It is to be noted, however, that the maximum sheen is developed by strong (macro) etching, which in the author's experience never produces angular oriented etching pits.

In the so-called "hatched" bands of many octahedrites the sheen usually is particularly marked. The hatching is due to a transformation structure described in Chapter XI, which gives rise to many planes along which the unequal attack of the etchant would be strong.

In granular kamacite the orientation of such transformation structures may vary in different grains because of the diverse orientation of the atomic planes of the original grains previous to transformation. Since the grains have a random orientation, the acicular transformation structure may vary from grain to grain, resulting in different etching effects and variations in sheen.

Sheen in vertical illumination.—The reason why sheen is not usually observed on microetched surfaces with vertical illumination is primarily that the etching is too light to make an appreciable attack along the atomic planes. With strong microetching certain kamacite areas or grains are likely to exhibit a sheen, which, however, does not change when the specimen is rotated; bright and dark areas appear the same in any position.

This is consistent with the foregoing explanation of the origin of the sheen. If the atomic planes are cut obliquely much of the light is reflected away regardless of the position of the specimen, and the area therefore appears dark; while if the planes are normal to the surface the effect of the etchant along the lines of such planes would be slight and the light to a considerable extent would be reflected upward in all positions, causing such an area to appear bright. A very slight obliquity in the illumination may make a dark surface turn bright.

The sheen observed under vertical illumination is faint in comparison with the brilliant effects seen in oblique light on a macroetched specimen.

Some areas show no sheen with oblique light. This presumably is due to the fact that in such areas the surface is parallel with, or normal to, the atomic planes; in which case the attack of the etchant would be uniform and its effect upon the surface would appear the same regardless of the direction of the light.

Swathing kamacite.—Nodules of troilite in octahedral irons are often enclosed by a narrow band of kamacite, unrelated to the surrounding octahedral structure, which abuts against it unconformably. This has been termed swathing kamacite. It differs little from the adjoining kamacite, though it does not show the grain boundaries that may be present elsewhere.

Similar bands of kamacite, apparently originating in the same manner, often surround troilite inclusions in hexahedrites and ataxites. Owing to the absence of the strongly contrasting Widmanstätten structure, they are often barely noticeable. They may often be distinguished by the absence of minute inclusions that are abundant in the surrounding mass.

Swathing kamacite is also found around needles (lamellae) of troilite, as well as around needles of schreibersite.

The manner of production of swathing kamacite is discussed in Chapter XV. Numerous examples are illustrated in the plates.

Cold-working.—Although with microetching kamacite ordinarily appears perfectly clear, very light etching (5 or 10 seconds) often causes a grayness that disappears again with a longer application of the etchant. This is probably due to "cold-working"—that is, to a slight dragging of the surface of the soft metal by the abrasive.

When kamacite appears in bands, lamellae, or particles associated with harder structures, the softer metal naturally would be susceptible to cold working, which often causes some difficulty in obtaining a perfect surface. The removal of the slight film of cold-worked metal by further etching would account for the disappearance of the gray color. These effects are well shown in plates 14, 30.

Occasionally in granular irons certain grains will be darkened by cold-working, while adjoining grains are not; which might seem paradoxical, inasmuch as the grains are identical in composition and hardness. It may be explained, however, by the fact that the atomic planes of the grains are variously oriented, and in certain of them the planes are in such positions as to be less resistant to the action of the abrasive. The same effect is often observed in pure artificial iron and in certain steels.

Taenite.—Taenite (gamma nickel-iron), composed of iron and nickel in varying proportions, is tin-white, elastic, and usually magnetic. It is easily distinguished from kamacite by its white color and its resistance to etchants, it being practically insoluble in cold dilute acids. It is soluble in concentrated hydrochloric and nitric acids, and like kamacite it reduces copper from solutions of copper salts.

Although in the literature of meteorites taenite is always described as strongly magnetic, that property would depend upon its composition. A nickel-iron alloy with less than about 26 percent nickel is magnetic at room temperature, and the same is true if the nickel content is more than about 30 percent; but between those limits such an alloy is nonmagnetic. Taenite being of widely varying composition, depending on the conditions of the phase transformations that produce it, there naturally must be many cases where a given sample would fall within the nonmagnetic range of composition.

In hardness taenite usually differs little from kamacite, a needle scratch appearing the same across both. Its hardness, however, also varies according to its composition. The Brinnell hardness curve for nickel-iron indicates that when the nickel content is about 5 to 15 percent the hardness of the alloy is only 5 to 10 percent greater than that of iron, and the same is true when the proportion of nickel exceeds about 20 percent; but between these percentages the hardness becomes about 18 percent greater than that of iron. Thus, except for a narrow range of composition, the difference in hardness between taenite and kamacite would hardly be distinguishable by any ordinary hardness test. Kasé (1925) verified experimentally that the hardness of kamacite and taenite is virtually identical.

Occurrence of taenite.—In octahedral irons taenite appears typically as lamellae, from fairly thick and visible to the eye, to very tenuous. In a regular octahedral structure they are prevailingly fairly straight and uniform, but they are often irregular. Not infrequently in the coarsest octahedrites they are absent, the kamacite bands being in contact. Conversely, in very fine octahedrites the kamacite bands become narrow and the taenite lamellae broad and thickly crowded. Taenite also occurs as needles, as fine or coarse skeletal growths, in large irregular masses, and in minute particles.

Taenite lamellae very often enclose rounded or elongated areas of darker color, the darkness increasing toward their centers, which is observable both with macroetching and with microetching (pl. 8, fig. 2; pl. 13, fig. 4; pl. 35, fig. 1). Such taenite is termed by German writers "fleckig,"which is commonly translated as "spotted," though darkened or shaded would better describe it. The appearance is due to incomplete transformation, resulting in an imperfect separation of taenite and kamacite. (See chapter XI.)

Composition of taenite.—Taenite is rarely homogeneous in composition. The shaded areas referred to, which are very common, are from the manner of their formation poorer in nickel than the clear peripheral portions. This is definitely proved by the process of quantitative coloration described in Chapter XVII. Sodium picrate etching also reveals that taenite lamellae, though appearing homogeneous with ordinary etching, often have borders rich in phosphide and even may be phosphide-rich throughout.

Because of such variations and the mechanical impossibility of isolating a hypothetically "pure" taenite, it is impossible to establish any definite composition by analysis. The nickel content has been fixed by various analysts at percentages all the way from 13 to 48, corresponding with formulas ranging from FeNi to Fe_7Ni (Farrington, 1907).

In view of the fact that taenite lamellae show lighter and darker zones, and from a study of 26 analyses, Buddhue (1938) suggests two forms, a lighter nickel-richer and a darker nickel-poorer, the former containing about 34 percent nickel and corresponding with Fe_2Ni, while the latter is about Fe_6Ni. It seems unsound to the author, however, to postulate any definite composition for taenite on the basis of chemical analysis, because from the manner of its formation the nickel content necessarily varies widely. Taenite must be regarded as a nickel-rich alloy of variable composition. This subject is discussed more fully in Chapter VIII.

Plessite.—Plessite is the structural component of the fields in octahedral irons. Such fields usually are bordered by taenite, and their structure is infinitely varied. Plessite is of two types, commonly designated as light or normal and dense or dark (termed by Pfann microplessite). The former is a relatively coarse, often macroscopic, combination of kamacite and taenite; the latter a very fine structure appearing black and homogeneous with low magnification.

The coarsest types of light plessite often show skeletal growths of taenite, referred to by German writers as combs (Kämme), parallel with one or more of the surrounding octahedral planes. Sometimes fields are occupied by minute bands of kamacite, reproducing in miniature the general octahedral structure.

Another familiar type consists of relatively coarse lamellae, roughly parallel though wavy and irregular. The taenite lamellae are often thickened at their ends. Still another type consists of coarse or fine rounded or tubular kamacite particles, resembling a wall of masonry.

The various types of plessite are illustrated in the plates.

In some fine octahedrites extensive plessite fields consist of kamacite or dense plessite filled with minute parallel threads of taenite. Such fields glisten brilliantly with macroetching when the light falls at right angles to the threads.

A finer structure is seen in fields wherein the taenite appears in minute particles. In clear fields of granular kamacite the taenite often segregates in droplike form at the junction of grain boundaries. Often fields are strewn with elongated particles of taenite, whose direction may be oriented, and if the kamacite is granular, oriented diversely in different grains. In such fields the kamacite often shows Neumann lines and an oriented sheen. In granular fields the orientation of the lines and of the sheen usually varies in different grains.

When the minute rounded particles of taenite are very numerous the plessite grows darker, often showing lighter and darker bands.

Dense plessite.—While light or normal plessite fields show an endless variety of structure, the dense plessite is of one general type—minute taenite particles in a matrix of kamacite, forming a dark or black groundmass resolvable only at fairly high magnification. The particles are often more or less oriented, frequently producing a banded effect, and there are many examples transitional between the darker banded plessite and the dense type. Often a light field encloses one or more areas of dense plessite, with boundaries parallel with those of the field.

Dense plessite appears black with macroetching, the fine division of its components producing the dark effect characteristic of metallic powders. The fact that with microetching and vertical illumination such areas may still appear black, and that minute kamacite particles in taenite also appear black although kamacite in larger areas is clear, is explainable in this way: An area of clear kamacite etches uniformly, presenting no visible contrasts, whereas in a field filled with finely divided kamacite and taenite the etchant attacks more strongly along the interfaces of the two components. Thus the interface of any inclusion is darkened, whatever its nature may be, and if a particle is minute the darkening produces the effect of a black dot.

Occurrence of plessite.—Coarse plessite is characteristic of the coarser octahedrites. Exceptionally it occurs in octahedrites that are classed as fine (e. g., Bear Creek) but not in the finest. In some of the coarsest octahedrites it is wholly absent. Osseo, for example, shows neither plessite nor taenite.

Logically it would seem that plessite also should be absent in hexahedrites, which contain even less nickel than the coarsest octahedrites, and in fact that has hitherto been assumed. Plessite has been regarded as exclusively an octahedral structure, and the absence of both plessite and taenite as characteristic of hexahedrites. The author, however, has found numerous coarse plessite fields, with taenite borders, in Otumpa, which is a typical hexahedrite both as to general structure and composition. In Sierra Gorda, a typical "normal" hexahedrite with the low nickel-cobalt content of 5.83 percent, a small area of plessitic structure was found in which taenite is segregated both as a border and in oriented inclusions (pl. 78). As a rule plessite fields in the coarsest octahedrites that approach hexahedrites in composition and character are irregular and atypical.

Dense plessite is characteristic of the finer octahedrites, and in the finest it is the chief component. In the coarser types it occurs sparingly and in small areas. Its structure is substantially the same as that of nickel-rich ataxites. The manner of production of such structures is discussed in Chapter XII.

IV. ACCESSORY CONSTITUENTS OF METEORIC IRON

Nonmetallic inclusions are found abundantly in meteoric irons, of which the commonest are troilite (FeS); daubréelite ($FeS \cdot Cr_2S_3$); schreibersite, a nickel-iron phosphide of varying composition; and, more rarely, the nickel-iron carbide known as cohenite $(FeNi)_3C$, iron oxides, and silicates. Only these will here be considered, as they are the only ones having any important relationship with the structure of such irons. Their general character will first be noted, and their metallographic aspects will be discussed more fully in later chapters.

Troilite.—Iron sulphide, the most familiar inclusion in meteoric irons, was recognized by the oldest writers and was named in 1863 by Haidinger in honor of Domenico Troili, who in 1766 mentioned an iron sulphide found in a stony meteorite. It is common in both meteoric stones and irons, but it occurs in much larger masses in the irons, sometimes in nodules 2 or 3 inches in diameter. It appears commonly in droplike inclusions or in irregular rounded forms. It shows a microstructure of polygonal grains (pl. 49).

In octahedral irons troilite is occasionally observed in the form of scattered plates or lamellae with a definite cubic orientation unrelated to the octahedral pattern. These are known as Reichenbach lamellae (pl. 47).

Troilite is easily recognized by its bronze-yellow, brassy, or brownish color, its low hardness (4), and the readiness with which it is attacked by acids, which produce an odor of hydrogen sulphide. It may also be identified by a sulphur print, as explained in chapter XVII. It is nonmagnetic and its streak is black. It does not reduce copper from solutions of copper salts.

In composition troilite is substantially identical with terrestrial pyrrhotite, though the composition of the latter is $Fe_{11}S_{12}$, while that of troilite is probably FeS. Troilite is not found in terrestrial rocks.

Troilite crystals.—Until recently troilite had rarely been found to show a definite crystalline form. Rose found imperfect microscopic crystals in a stony meteorite, from which he determined that its crystallization is hexagonal, and similar minute crystals with measurable angles were found by other investigators (Meunier, 1884; Cohen, 1894, p. 190).

A well-developed macroscopic crystal was found by the author in Seneca Township (1939), and shortly afterward Nininger (1939) described similar fairly well defined macroscopic crystals in Monahans. More recently the author found relatively large microscopic crystals of great perfection and beauty in Otumpa (pl. 48).

Daubréelite.—Daubréelite, discovered by Smith in 1876 in Coahuila, and later observed in many irons, is an iron-chromium sulphide not found in terrestrial rocks. Its composition is $FeS{\cdot}Cr_2S_3$.

It is commonest in hexahedrites, much less common in other irons. It usually is associated with troilite, adjoining or bordering it, or intergrown with it. Not infrequently it crosses the troilite in parallel bands (pl. 48).

Daubréelite is black or dark brown, has a black streak, is very brittle and not magnetic. Unlike troilite, it is said not to be attacked by hydrochloric acid, though dissolved by nitric acid. Under the microscope it is likely to show a chipped or broken surface because of its brittleness. Where bands of troilite and daubréelite alternate, the former appears darker in color.

Its crystallization is not known, but it tends to assume quadrangular forms.

Schreibersite.—The most interesting accessory constituent of meteoric irons is the iron-nickel phosphide schreibersite, both because of its peculiar and varied forms and because of its important metallographic aspects. It appears in many forms, illustrated in the plates—as small microscopic crystals in the shape of squares, rhombs and short quadrangular baguettes, termed rhabdites; as needles, sometimes stout and again exceedingly fine and long; as lamellae or elongated bodies scattered along the boundaries of octahedral bands in place of taenite, or alternating with similar bodies of taenite; as larger irregular inclusions of all shapes; and as a dispersion of exceedingly minute particles. Rhabdites originally were described and named as a substance different from other forms of schreibersite. Its crystaline habit, long surmised to be tetragonal, was so established by Wherry (1917) and confirmed through X-ray analyses by Heide, Herschkowitsch, and Preuss (1932).

Schreibersite is present to some extent in the majority of meteoric irons, and in many it is a conspicuous component. Rhabdites are especially plentiful in hexahedrites. They may be uniformly scattered, or they may appear in certain areas or grouped in parallel zones. Often they appear to be scattered with no definite arrangement, but they probably are oriented. In octahedrites Brezina found schreibersite lamellae to be disposed along dodecahedral planes, but that conclusion seems erroneous (p. 81).

As pointed out in Chapter II, an apparent needle is a cross section of a lamella. It is very unlikely that the plane of the section ever would intersect a true needle lengthwise if it were fine and of any considerable length. True needles, if they exist, would probably be short and stout. It is impossible to determine definitely whether an apparent needle is such, or a section of a lamella, without examining the surface after successive polishings.

That rhabdites are small crystals, and not cross sections of long prismatic crystals or needles, is apparent from observation and is confirmed by the fact that heating changes them to shapeless rounded bodies and also by the fact that repolishing causes some to disappear and new ones to appear.

Very fine phosphide particles in iron that has not been reheated, though appearing as dots, are probably not rounded but normally angular. The etching attack around the particles is very rapid, leaving a relatively wide-etched interface between the crystallite and the surrounding kamacite, which causes the more minute ones to appear black even with high magnification.

In its larger forms schreibersite occurs as apparent needles, sometimes several centimeters long; also in rounded, droplike, dendritic, graphic, jagged, and sprangling shapes, sometimes reaching dimensions of an inch or more. It is often associated with troilite, adjoining it or surrounding it, and sometimes with graphite.

Owing to its brittleness schreibersite, except in small inclusions, is apt to suffer surface chipping in polishing, causing black spots. Minute phosphide particles also pull out in polishing, causing black dots to appear quickly with even the lightest etching.

Properties of schreibersite.—Schreibersite is tin-white, like taenite, but the eye soon learns to recognize it easily. It is readily distinguished from taenite by its great hardness (6.5), a needle making no impression on it while producing a deep scratch on the adjacent taenite or kamacite. It is magnetic and readily fusible, its melting point being about 1,000° C.

It is insoluble in cold dilute acids and therefore is unchanged with ordinary etching. It is insoluble in copper ammonium chloride and does not reduce copper from copper salt solutions—differing in both respects from taenite, and also from cohenite, which presently will be mentioned. After boiling in nitric acid the addition of ammonium molybdate produces a yellow precipitate, which also is not the case with cohenite.

An unfailing test for schreibersite is etching with boiling neutral sodium picrate, which blackens it but does not affect cohenite or the metallic components.

Schreibersite inclusions are often surrounded or invaded by oxide. Sometimes aureoles of oxide around rhabdites or needles might appear to be due to diffusion of the phosphide as a result of reheating; but if such were the case the rhabdites would not be likely to show perfect crystalline forms, and the aureoles if due to diffused phosphide would be invisible with ordinary etching. The oxide, however, appears black with any etching and is also visible on an unetched suface. Rhabdites thus surrounded by oxide are shown in plate 53.

Composition of schreibersite.—The composition of schreibersite, as indicated by analyses, varies greatly. It is essentially a nickel-iron phosphide, with usually some cobalt. The commonly accepted formula is $(Fe\text{-}Ni\text{-}Co)_3P$, although some analyses indicate the ratio of Fe-Ni-Co to P as 4, 5, 7, and even higher.

Higher ratios than 3 to 1 might possibly be explained on the supposition that the material analyzed was an iron-phosphide eutectic (pp. 79, 80), which without metallographic examination would not be distinguished from the pure phosphide. Such eutectics often contain droplets of rejected iron (pls. 58, 59), which would further increase their iron content.

Schreibersite is peculiar to meteorites. Terrestrial phosphides do not exist, as they become phosphates by the action of oxygen.

Occurrence of schreibersite.—The quantity of schreibersite in some irons is very considerable; thus pieces of Glorieta Mountain were found to contain 3 to 8 percent. This might seem inconsistent with the phosphorus content of that iron, which analyses indicate is not more than 0.36 percent. But inasmuch as the atomic weight of phosphorus is about 31, while the atomic weights of iron, nickel, and cobalt are between 55 and 59, an iron with 1 part of phosphorus would contain about 6½ parts of the "pure" phosphide. If the inclusions were an iron-phosphide eutectic, that ratio would be increased. It is also to be remembered that the phosphorus in meteoric irons, especially in octahedrites, is often largely concentrated in local areas.

Carbon.—Though carbon plays a subordinate role in the metallography of meteoric iron, it is of interest because of its abundance in some irons in the form of the carbide cohenite, and also because in rare instances it produces iron-carbon structures identical with some that are produced by carbon in artificial irons. Two instances of such structures are described in Chapter XV. It also occurs in the free form as graphite.

Free carbon in the form of graphite is not uncommon. It may occur as grains or lamellae, but most often as nodules, which sometimes reach dimensions of an inch or more (Cosby Creek, Magura, Smithville). It is often associated with troilite, adjoining or surrounding it, or intergrown with it (pl. 62). In Dungannon (pl. 62), which has the high carbon percentage of 0.532, the graphite is confined to small areas where it appears in meandering arborescent patterns.

Other irons showing high percentages of carbon are Canyon Diablo 0.417 percent (in certain spots), Savannah 0.475 percent, Seeläsgen 0.52 percent, and Cosby Creek 0.50 percent. Presumably the material analyzed was free from the larger graphite inclusions found in some of these irons.

Graphite is easily recognized by its characteristic appearance and softness and its visibility on an unetched surface. It does not show in a sulphur print, a test that helps to recognize quickly the presence of graphite in association with troilite, which it sometimes resembles in appearance.

Carbon in amorphous form is found along the boundaries of the very large grains of some granular hexahedrites.

Cohenite.—The carbon in steel and white cast iron does not occur as free carbon but as the carbide called cementite, Fe_3C. In meteoric iron the corresponding carbide is known as cohenite. It is nickel-iron carbide $(FeNi)_3C$; or, since some cobalt is usually present, perhaps $(FeNiCo)_3C$.

Cohenite is comparatively rare, having been found chiefly in a few coarse octahedral irons where it occurs in the form of imperfect, rounded, elongated crystals, exceptionally reaching dimensions of several millimeters. The rounded form of the crystals makes their angles difficult to determine, but Hussak (Cohen, 1903, p. 222) stated that they are isometric, and the same conclusion was reached by Heide, Herschkowitsch, and Preuss (1932), who stated that they are of the spinel type. That conclusion, however, seems open to question because of the fact that artificial iron carbide (cementite) is definitely orthorhombic, having been so determined by many investigators. Cementite and cohenite are identical, except that the latter (at least in some cases) apparently contains a small percentage of nickel.

Like schreibersite, cohenite is very hard (5.5 to 6), tin-white, brittle, magnetic, and insoluble in dilute acids and therefore unchanged by ordinary etching. Unlike schreibersite, it is infusible before the blowpipe, is soluble in copper ammonium chloride, reduces copper from solutions of copper salts, and gives no precipitate with ammonium molybdate.

Occurrence of cohenite.—Cohenite is found in comparatively few irons. It is abundant in Magura, Bendego, Wichita County, Beaconsfield, and Canyon Diablo (Cohen, 1894, p. 115; 1903, p. 221) and also in Cosby Creek, and it has been reported in a number of other irons.

It seems to be confined to areas of carbon enrichment, as the analyses of most of these irons show very small percentages of carbon. The first four mentioned by Cohen show percentages of 0 to 0.07. Canyon Diablo in one sample analyzed yielded the high carbon content of 0.417 percent, in another none. In Canyon Diablo cohenite sometimes is abundant over a considerable area, Cohen having isolated 10 percent from one sample, while in other areas none whatever was found.

In most of these irons the profusion of cohenite might seem inconsistent with the small carbon content shown by the analyses. Cohenite, however, is virtually identical with the cementite of artificial irons; and, inasmuch as the atomic weight of iron is 56 and that of carbon 12, one part by weight of carbon produces 15 parts by weight of cementite. The calculation is:

$$\frac{(3\times 56)+12}{12}$$

This striking ratio, together with the fact that there may be spots of carbon enrichment, explains why cohenite is abundant in Magura and Wichita County, although analyses of those irons have shown respectively only 0.03 and 0.0 percent of carbon.

Nickel in cohenite.—As nickel is not carbide-forming in artificial irons, metallurgists might well doubt the presence of nickel in cohenite. It has, however, been positively reported by a number of competent analysts who found the following percentages: Dafert in Bendego 2.20 percent; Sjöström in Beaconsfield 2.22 percent and in Wichita County 2.37 percent; Weinschenk in Magura 3.08 percent. In Canyon Diablo Fahrenhorst reported 1.77 percent nickel; Florence 0.13 percent and 2.21 percent; Tassin 2.47 percent, and in another analysis 2.21 percent of nickel and cobalt. These analyses were compiled by Farrington (1915).

These determinations would seem to establish the existence of an iron-nickel carbide. It is still possible, however, that the nickel thus found was not in chemical combination with carbon.

The rarity of cohenite may perhaps be ascribed to the graphitizing influence of nickel, which in nickel steels makes it easy to change the carbide (cementite) to graphite by a relatively short heating. Thus in meteoric irons the presence of nickel might tend to prevent the preservation of carbide by causing it to break down into graphite and iron.

It is noteworthy that cohenite apparently has not been found in the higher nickel (medium and fine) octahedrites or in nickel-rich ataxites, but only in the coarse and coarsest octahedrites in which the nickel content is not more than about 7 percent. (The percentage of 10.01 reported in 1860 in Wichita is probably incorrect.)

It has already been mentioned that in most irons, notably in Canyon Diablo, the occurrence of cohenite is apt to be localized, it being abundant in some areas and absent in others. It may be significant that in Canyon Diablo there is also a surprising variation in nickel content. Moissan reported 3.07 and 5.07 percent from different parts of the same specimen, and in another specimen 1.08 and 7.05 percent. Other analyses have shown 3.94, 7.94, 5.78, and 9.25 percent. It might be instructive if we could know whether the very low percentages were found in areas where cohenite was abundant.

Identification of cohenite.—It is quite possible that cohenite is commoner than it has been supposed to be, because it resembles schreibersite so strongly that the difference is not easily recognized. Even so great an authority as Vogel (1927) illustrates a sample of Canyon Diablo in which inclusions of cohenite are referred to as schreibersite.

In hardness and in appearance on a polished surface they are practically identical, and their behavior is the same with any ordinary etching. Their very close resemblance is shown in plate 64, where the two happen to be in juxtaposition. Blowpipe tests, and those of ammonium molybdate and copper ammonium chloride, are not easily applied.

One indication that inclusions may be cohenite is their arrangement parallel with the octahedral structure. In Canyon Diablo and Wichita County, for example, there is a profusion of elongated cohenite bodies in the kamacite bands. Schreibersite inclusions do not show such an arrangement.

A test easily applied to the macrostructure is the reduction of metallic copper from a salt of that metal. This is most readily done before micropolishing, with a fairly weak solution of copper sulphate, slightly acidulated. (The action of Stead's, Le Chatelier's, and other special reagents used in microexamination is too slow.) On application of the solution a red film of copper quickly flashes over the surface of the iron. If cohenite is present it is covered with the film of copper, but schreibersite inclusions are not.

To identify cohenite on a microetched sample, the author has found the most satisfactory tests to be electrolytic etching with alkaline sodium picrate and the use of Murikami's reagent. These methods, which darken cohenite but not schreibersite, are described in chapter XVII. Electrolytic etching with chromic acid, a standard test for carbide in artificial irons, proved less satisfactory.

Finally, a test that should infallibly distinguish the two is spectroscopic analysis, which reveals as little as 0.01 percent of phosphorus. If the spectrum of a doubtful inclusion shows no phosphorus lines it cannot be schreibersite.

Oxides.—Iron oxides are often present in meteoric irons, not as a primary constituent but as a product of oxidation, either during atmospheric flight or by weathering.

The commonest type is the hydroxide (limonite), which is the result of weathering. Few iron meteorites are free from it, unless freshly fallen. It forms a brown-black crust and penetrates more or less into the mass. In some cases the kamacite is oxidized, but the taenite lamellae remain unchanged, preserving the outlines of the octahedral pattern. In other cases the iron is wholly changed to limonite with only faint traces of its original structure. The hydroxide tends to penetrate octahedrites along the planes of the Widmanstätten pattern and also along grain boundaries, and sometimes along the planes of Neumann lines. See plate 67.

Magnetic or ferrosic oxide (Fe_3O_4 or $FeO.Fe_2O_3$), which is mineralogically identical with magnetite, is formed by the superficial fusion and oxidation of the iron during its flight through the atmosphere, which produces the fusion crust often observed on iron meteorites. The oxide is driven into the cracks that often are formed in the mass by stresses resulting from extreme atmospheric pressure during flight, and it occasionally appears as small rounded intrusions invading the surface slightly. It probably never occurs as pure magnetic oxide, as it naturally would carry in solution more or less ferrous oxide, iron, troilite, and schreibersite. This oxide, called by the earlier German writers Eisenglas, has a black, somewhat glassy appearance.

Oxides are easily recognized, being visible on an unetched surface. The magnetic oxide, however, sometimes is not easily distinguished from the hydroxide, except by the manner of its occurrence. Invasions of the former have rounded outlines and sharply defined edges, are generally independent of octahedral structures, and never show intergranular development. The contrasts in appearance are shown in plates 67–70. Intrusive oxide is apt to invade bodies of schreibersite because of its low fusibility.

A further discussion of intrusive oxide will be found in Chapter XIII.

Silicates.—A number of silicates are associated with meteoric iron. In mesosiderites (ironstones), transitional between stony and iron meteorites, they may form half or more of the mass. In pallasites, composed of nickel-iron and the silicate chrysolite, the silicate may form a groundmass in which bodies of iron are dispersed, or the iron may form a spongy mass filled with the silicate in the interstices, showing as a network upon a polished surface. In siderites (meteorites consisting wholly of iron) silicates occasionally occur as inclusions.

Of the silicates thus found in siderites the most common are chrysolite (olivine), anorthite, and some members of the pyroxene group. These also are found in mesosiderites. Forsterite occurs in the Tucson ataxite (pl. 20), but according to Cohen it has not been observed in other irons. In the unique Four Corners octahedrite there are abundant inclusions of pyroxene. Blebs of glass are occasionally observed in meteoric irons.

Minor constituents.—The foregoing are the more important accessory constituents of meteoric irons, but there are numerous others that are of interest from the standpoint of the general science of meteoritics. These include the diamond, of which small crystals and particles have been observed, notably in Canyon Diablo; chromite, which occurs not infrequently as grains and sometimes in nodules; and the ferrous chloride lawrencite ($FeCl_2$), which is reported to have been observed in the solid state but which is deliquescent and usually manifests itself in an exudation of clear greenish drops.

Lawrencite is not a factor in the structure of meteoric irons except by reason of its destructive action in causing rust and disintegration. By the action of the air it turns to ferric chloride ($FeCl_3$) and ferric hydroxide (limonite). The ferric chloride in contact with the still unaltered iron is reduced again to the ferrous chloride. Thus the process is continuous, and as it is accompanied by an increase in volume the iron may become wholly altered and disintegrated unless it is kept under oil. Lawrencite is the bane of curators and collectors. If an iron definitely contains lawrencite, no amount of lacquering seems to protect it; the only recourse is immersion in oil.

V. ARTIFICIAL IRONS

A brief outline of the metallography of artificial irons is a necessary preliminary to the study of the structures of meteoric irons—partly because of the important analogies involved and partly because it is necessary to use the methods and terminology of the technical metallographers.

Iron and its alloys.—Absolutely pure iron is perhaps unknown, but iron prepared by the electrolytic process approaches chemical purity, and the purest iron produced commercially contains only negligible amounts of other substances. Iron (substantially free from admixture) as a structural component is known in metallography as ferrite, and its structure under the microscope is a network of irregular polyhedral grains (pl. A). Its melting point is about 1,530° C.[3]

Most artificial irons (like all natural ones) are alloys. The most important added constituents are carbon (in steels and cast irons) and the various metals used in alloy steels, of which nickel is the only one that is important in meteoric irons. Nickel is close to iron in its chemical and physical properties. Its melting point is about 100 degrees lower than that of iron, and it is soluble with iron in all proportions.

Carbon occurs in two forms—as free carbon (graphite) and as iron carbide (Fe_3C), which is termed cementite. It is in the latter form that carbon appears in steels, which contain less than about 2.5 percent of carbon, and in white cast iron, which contains more than that percentage. In gray cast irons, which often contain a still higher percentage, the carbon may be partly free and partly combined, or it may appear chiefly as graphite in irregular leaflike flakes. See plate B.

At its melting point iron can dissolve about 5 percent of carbon; but about 4.5 percent is the maximum carbon content actually produced in cast iron—unless some component be present (such as manganese) that increases the solubility of carbon.

Phases of pure iron.—Iron (and other metals) in cooling pass through certain allotropic transformations known as phases, in which lattice structure, crystalline habit, and magnetic properties undergo changes. These transformations, with their modifications by reason of thermal conditions and added components, produce the great variety of structures and properties in natural and artificial iron alloys.

The metal begins to solidify at about 1,530°, forming first dendritic crystals and then grains. This is the uppermost or delta phase of the solid state. Delta iron is cubic in crystallization, with a body-centered space lattice. This phase continues, as the metal cools, to 1,400°, when the grains of delta iron change to gamma iron, with a face-centered cubic lattice. At 910° another transformation takes place, when the grains of face-centered gamma iron become body-centered cubic alpha iron. This, like all allotropic changes, is accompanied by recrystallization, the gamma grains changing into smaller alpha grains. This is the last structural change, the iron now having reached its final microscopic structure; but at 760° a further change in physical properties takes place, the iron becoming ferromagnetic. These processes are indicated diagrammatically in figure 1.

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[3] All temperatures are centigrade unless otherwise stated.

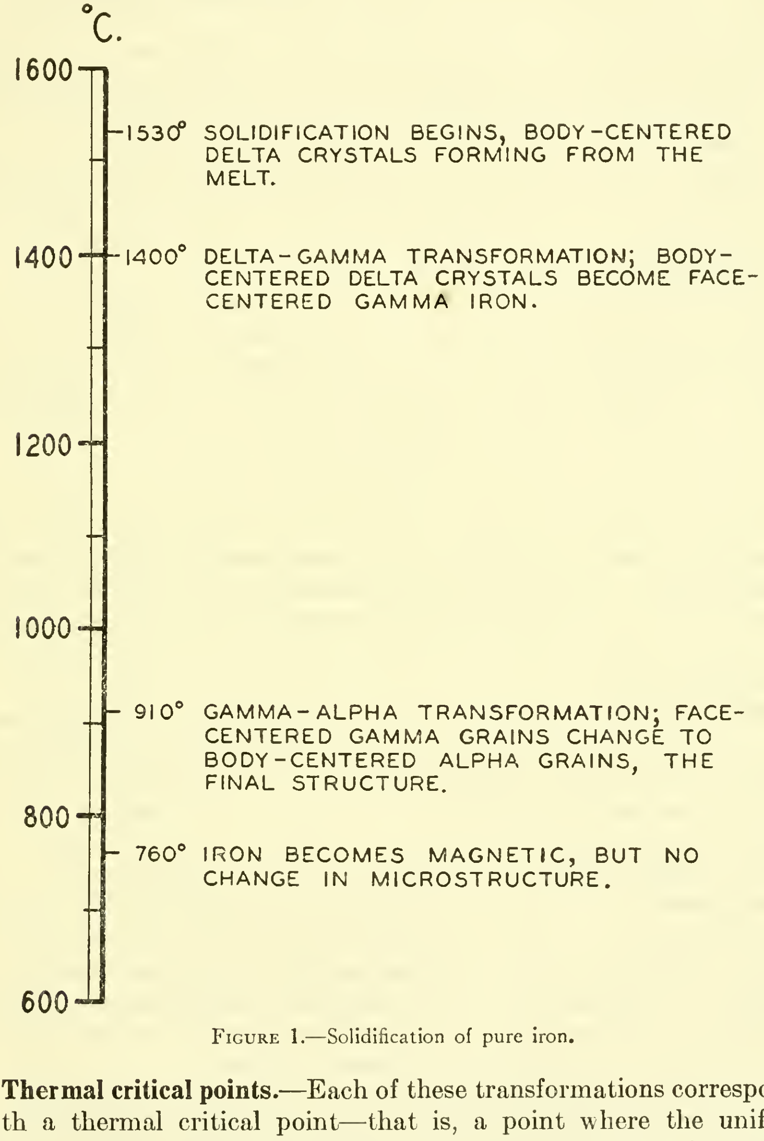
°C.
1600
1400
1200
1000
800
600
1530° SOLIDIFICATION BEGINS, BODY-CENTERED DELTA CRYSTALS FORMING FROM THE MELT.
1400° DELTA-GAMMA TRANSFORMATION; BODY-CENTERED DELTA CRYSTALS BECOME FACE-CENTERED GAMMA IRON.
910° GAMMA-ALPHA TRANSFORMATION; FACE-CENTERED GAMMA GRAINS CHANGE TO BODY-CENTERED ALPHA GRAINS, THE FINAL STRUCTURE.
760° IRON BECOMES MAGNETIC, BUT NO CHANGE IN MICROSTRUCTURE.

Figure 1.—Solidification of pure iron.

Thermal critical points.—Each of these transformations corresponds with a thermal critical point—that is, a point where the uniform rate of cooling is briefly retarded, after which it resumes its regular rate of progress. These points are designated, in downward order, in the following manner: A_4 (delta to gamma, 1,400°); A_3 (gamma to alpha, 910°); and A_2 (magnetic transformation, 760°).[4]

If the iron contains carbon there is another critical point at 723° called A_1. The points A_1 and A_3 approach each other rapidly with even a very slight admixture of carbon, and when the percentage reaches 0.80 they merge—the point then being designated commonly as A_1.

Hysteresis.—In pure iron the critical points mark practically definite temperatures; but in alloys there is a more or less pronounced lag (hysteresis) in the transformations, which thus take place somewhat above these temperatures on heating and somewhat below them on cooling. The positions of the thermal critical points on heating are designated as Ac_1, Ac_3, and Ac_4 (the *c* standing for the French word *chauffage*), and on cooling as Ar_1, Ar_3, and Ar_4 (French *refroidissement*).

The admixture of certain metals lowers the Ar_3 point, and the presence of nickel in particular not only greatly depresses the Ar_3 point but also greatly increases the gap between the Ac_3 and Ar_3 points. This fact, which is further discussed in Chapter VIII, has a bearing upon the structure of meteoric irons.

VI. ALLOYS

To appreciate the complex nature of iron meteorites it is necessary to consider them as having an origin somewhat similar to that of artificial alloys. They are essentially natural nickel-iron alloys. Hence, an outline of the general physical-chemical relationships of alloys is here given as an introduction to the discussion of the physical chemistry of meteoric iron.

Solid solutions.—A liquid solution is a complete and homogeneous merger of its components, though not in definite proportions and without any chemical combination—e. g., salt and water. An exactly similar merger may exist in the solid state, forming what is known as a solid solution.

Most metals form solid solutions with one another, which are termed alloys, and they also may hold in solid solution various nonmetallic substances. This is true of meteoric nickel-iron, which forms solid solutions with phosphides, sulphides, and other substances.

The term "solid solution" has supplanted in English and French usage the earlier term "mixed crystals," although the latter (Mischkrystall) is the term still used by German writers.

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[4] There is a difference of opinion as to whether another phase, the beta phase, should be recognized between 700° and 910°. Most authorities take the view that the thermal critical point designated as A_2 at 760°, which is the magnetic transformation point, also marks the change between the beta and alpha phases. The question is not here important, however; for according to the authorities that recognize the existence of beta iron it is identical with alpha iron in that it is body-centered and cubic in crystallization, differing from it only in electrical conductivity and in magnetic properties. The structural transformations for pure iron therefore may be assumed to be from delta to gamma iron at A_4 and from gamma to alpha at A_3.

Most structures, both in natural and artificial irons, develop in the solid state, but at temperatures high enough to give the solid solution the necessary atomic mobility. When the temperature has fallen to a point where diffusion practically ceases, structural changes also practically cease.

Solidification of alloys.—At its melting (or freezing) point a pure metal passes directly from the liquid to the solid state. The same is not true of an alloy, that temperature only marking the point where it becomes completely liquid on heating, and where solidification begins on cooling.

At the beginning of solidification the liquid alloy becomes pasty from the incipient formation of crystals. The line where this process begins, and the line where it ends and the alloy has become completely solid, are termed respectively the liquidus and the solidus.

As the mass continues to cool, though it has become solid, it is not yet rigid, and its continued atomic mobility makes possible various changes and rearrangements of its crystalline structure. It is to this process that the varied structures of meteoric iron are chiefly due.

Eutectics; eutectoids.—An alloy solidifies at varying temperatures, according to the proportion of its components. A certain proportion results in the lowest fusion point, often much lower than that of either of its components. For example, silver melts at 962° and copper at 1,084°, but an alloy of 72 percent silver and 28 percent copper melts at 778°. This lowest fusion point for a given alloy is termed its eutectic temperature, and the combination in that proportion is called the eutectic of its components.

For iron and carbon the eutectic proportion of carbon is 4.3 percent, and an iron-carbon alloy of that composition solidifies at 1,130°. It is called eutectic cast iron (pl. C).

The terms eutectic and eutectoid should not be confused. A eutectic arises directly from the melt; it marks the eutectic temperature—the point where the alloy passes directly from the liquid to the solid state without going through any intermediate phase change. A eutectoid arises in the solid state, the product of a rearrangement of the components by atomic diffusion.

In each case the process is completed at a certain fixed temperature, and the structure consists of two components with definite compositions. Indeed, the two structures are essentially the same, except for the fact that the eutectoid arises in the solid state.

While the eutectic point for iron and carbon is 1,130° and the eutectic ratio 4.3 percent carbon, the eutectoid temperature is 723° and the eutectoid ratio 0.80 percent carbon. The eutectoid structure produced at that temperature is called pearlite, a very finely laminated aggregate of ferrite and cementite (pl. A).

True eutectoid structures do not occur in meteoric iron, but there are structures that approximate them, for which the author suggests the designation paraeutectoid.

Plates A, B, and C show the eutectic and eutectoid structures of artificial iron-carbon alloys, and many examples of paraeutectoid structures will be found among the illustrations of nickel-rich meteoric irons.

Phase changes in alloys.—It has already been pointed out that an alloy, unlike a pure metal, does not solidify instantly on cooling but passes through a range in which the liquid and solid phases coexist. There are differences in the other phase changes of an alloy, as compared with those of a pure metal. For example, pure iron on cooling passes directly from the delta to the gamma phase, and from the gamma to the alpha. An alloy of iron, on the other hand, does not change directly from one phase to the next but at each such transformation passes through a thermal range in which both of the phases temporarily coexist. This range is sometimes termed a miscibility gap (Mischungslücke). The position and the width of such a range or gap vary with the proportions of the alloying components.

Phase equilibrium.—The fact that phase changes in an alloy are different from those in a pure metal is the basis of the "equilibrium diagram," an understanding of which is essential to the study of metallography.

An alloy is stable when either its temperature or the proportion of its components may vary without producing any structural change. But there are certain intermediate thermal ranges in which (if it be a binary alloy) two phases coexist—one rich in the component X, the other in the component Y. In such a range the alloy is unstable, for a variation in either temperature or composition causes a change in the two phases and therefore in the structure.

Equilibrium in an alloy has been defined as a state of rest, in which neither chemical change nor atomic transformation is taking place. It would be more strictly accurate to say that the alloy is in equilibrium when the tendency to the separation of the two phases is in balance. Thus in an unstable range there is equilibrium at any given point representing a certain temperature and composition.

With an alloy of a given composition, in which two phases are present, the composition of the phases must vary as the temperature varies, in order that the two may at all times be in equilibrium. The beginning and the end of the transformation mark the thermal range within which such a shifting of phase compositions takes place.

Equilibrium diagrams.—As the positions of the various critical points in an alloy vary according to the proportion of its components, these ranges of temperature vary in width as the composition changes. An equilibrium diagram shows the phase corresponding with any given combination of temperature and composition. It is constructed by determining all the critical points for a given alloy in all proportions of composition, then plotting them to form a diagram in which the ordinates represent temperatures and the abscissae the percentages of the components. Lines are then drawn connecting all the A_1 points, A_3 points, etc. Such diagrams are also called constitution diagrams.

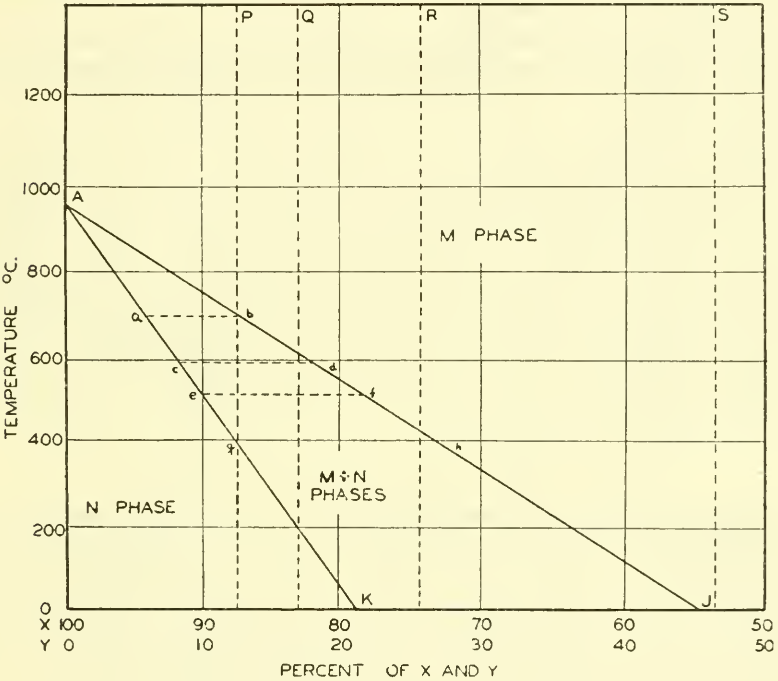

FIGURE 2.—Schematic equilibrium diagram.

Figure 2 is an equilibrium diagram in its simplest form for a hypothetical alloy of X and Y, a binary alloy, having two phases M and N, showing the position of the transformation points for all temperatures and compositions. The line AJ represents the beginning of the M–N transformation, the line AK the end of it.

Transformation of a typical alloy.—Assume that the alloy in the proportions P has solidified at some temperature above 1,000°. It is now a solid solution of X and Y in the M phase. On further cooling it continues unchanged to 700° where the M–N transformation starts. It has been homogeneous, but now it starts to become a mixture of the two phases M and N. Since these phases must remain in equilibrium, as the temperature falls the proportion of the N phase must increase in comparison with the M phase. The lowering of temperature also is marked by a progressive change in the composition of both the newly formed N phase and of the gradually disappearing M phase.

Just below 700° two phases coexist—the N phase of the composition *a* (richer in X) and the M phase of the composition *b* (richer in Y), the mixture being almost wholly in the M phase.

At 600° these compositions have shifted respectively to *c* and *d*, the two phases about equally divided; at 500° to *e* and *f*, the N phase now strongly predominating.

At 400° the transformation is completed; the alloy is now wholly in the N phase, the last disappearing traces of the M phase having the composition *h*. From this point downward the alloy remains in the N phase.

With the proportions Q, the transformation begins just below 600°, and the same shifting of phase compositions ensues, until at 200° the last of M disappears and the alloy is wholly in the N phase. With the composition R, the M–N transformation begins a little above 400° and there still is a mixture of M and N at room temperature. With the proportions S there is no transformation, the alloy being in the M phase throughout, from the melt to room temperature.

The foregoing outline describes ideal equilibrium conditions, which are never wholly attained.

VII. THE IRON-CARBON SYSTEM

The iron-carbon diagram.—Figure 3 represents in simplified form the equilibrium diagram of iron-carbon alloys. It omits the brief delta-gamma transformation (from 1,530° to 1,400° and confined to irons with less than 0.35 percent carbon), and it also omits the debatable beta phase, which has no practical application in this discussion, showing only the gamma-alpha transformation. The corresponding transformation in nickel-iron alloys produces all the primary structures of meteoric irons.

As shown by the diagram, an iron containing carbon instead of solidifying directly from the melt, as does pure iron, passes through a transitional zone ACB, in which the liquid is mingled with crystals of a solid solution of carbon in gamma iron (termed in metallography austenite) in a pasty or mushy state. If it contains less than 0.80 percent carbon, on passing the AC line (and now solid) it is in the gamma phase (austenite). On crossing the A_3 line at DE it enters another transitional zone DEF, in which the solid solution is a mixture of gamma and alpha phases. Finally at FE, the A_1 line, it has completely changed into alpha iron (ferrite) plus Fe_3C (cementite).

With no carbon the final product would be homogeneous granular ferrite; but when an iron-carbon alloy with less than 0.80 percent carbon in solution in cooling crosses the line DE (the A_3 line), grains of pearlite (the eutectoid of ferrite and cementite) appear among the ferrite grains (pl. A, fig. 2). This is hypoeutectoid steel.

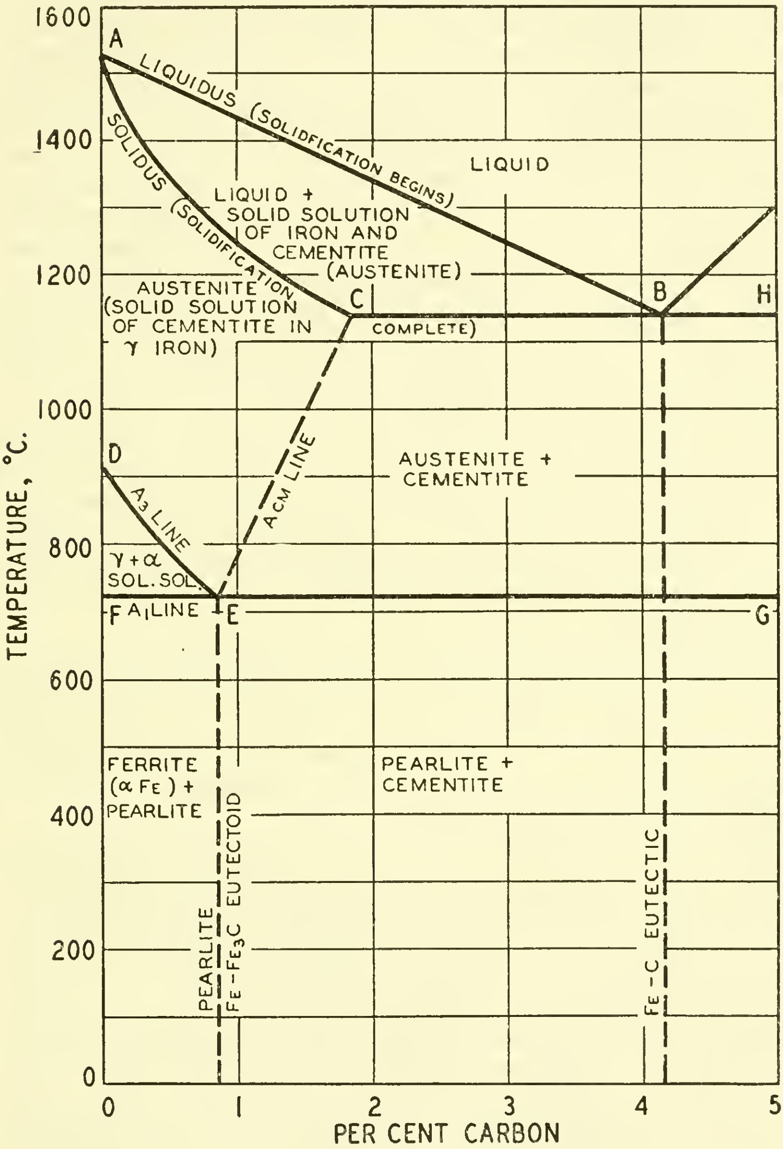

FIGURE 3.—The iron-carbon equilibrium diagram.

As the percentage of carbon rises, the areas of pearlite increase, until at 0.80 percent carbon, where the A_3 and A_1 lines coincide, the alloy passes directly from the gamma to the alpha phase plus Fe_3C as the eutectoid pearlite. This is eutectoid steel (pl. A, fig. 4).

At the point E on the diagram the line EC begins, marking the limit of solubility of cementite in austenite. It is called the A_{cm} line. At this line the austenite holds in solution all the cementite that it can, and on crossing the line in cooling it begins to give up free cementite—that is, whatever cementite there may be in excess of the eutectoid ratio corresponding with 0.80 percent of carbon.

Thus an iron containing more than 0.80 percent of carbon on passing the line EC is no longer a groundmass of ferrite grains with segregations of pearlite, but a groundmass of pearlite with segregations of cementite. It is termed a hypereutectoid steel (pl. B, fig. 1).

When the carbon content exceeds about 2.5 percent the metal is no longer a steel but a cast iron, in which free carbon (graphite) may appear. If the carbon is all in combined form it is a white cast iron, consisting of cementite and pearlite (pl. B, figs. 2, 3). If part of the carbon is in the form of flakes of graphite it is a gray cast iron (pl. B, fig. 4). Whether the cast iron is white or gray does not depend wholly on its carbon content, but largely on its rate of cooling, although the carbon content is generally higher in gray irons. The development of graphite is greatly influenced by the presence of a small proportion of silicon, which is commonly present in commercial cast iron.

At the point B, with a carbon content of 4.3 percent, the eutectic ratio, the melt solidifies at 1,130°, the lowest point for an iron-carbon alloy. It solidifies directly, without passing through any transitional range in which the solid and liquid phases are mingled. The product is eutectic cast iron (pl. C, fig. 1), consisting of particles of pearlite in a matrix of cementite.

The iron-carbon diagram, as shown in figure 3, generally is not carried beyond 5 percent of carbon, but at temperatures above 1,130° iron may hold considerably more than that percentage of carbon (in the form of carbide) in solution. Therefore, to the right of the point B, if the diagram were extended, the line AB would rise to a temperature around 2,200° where iron may contain as much as 9.6 percent of carbon, the maximum that it can hold in solution in any conditions.

In an iron in which the content is less than about 0.01 percent of carbon at room temperature (0.0088 percent) the changes above described do not take place. It behaves as if it were carbon-free, and the final product on cooling is a homogeneous solid solution of carbon in ferrite, indistinguishable from pure iron.

This phase, which might be shown as an extremely narrow zone at the left side of the diagram, is omitted.

Martensite.—Three iron-carbon structures in artificial irons should be noted, because of their alleged limited development in certain meteoric irons, and also because of analogous iron-nickel structures which are often observed.

Pearlite is formed under equilibrium conditions of cooling, a perfect lamellar separation of ferrite and cementite. Martensite, troostite, and sorbite, however, are nonequilibrium structures, the products of cooling conditions which do not permit the normal formation of pearlite.

When a steel in the austenitic (gamma) range is cooled so quickly that the austenite cannot transform normally, it does not change to pearlite below the critical range, but to an intermediate or transitional phase termed martensite, appearing typically as plates in low-carbon steels (pl. C) and as needles in hypereutectoid steels. Their orientation, suggesting the Widmanstätten structure, is related to the octahedral planes of the gamma phase. Some writers refer to it as a supersaturated solution of carbon in alpha iron. Authorities are not in full agreement as to the exact nature and process of formation of this constituent.

True martensite should not be confused with the acicular or banded iron-nickel structure which resembles it, which is found in many meteorites (see Chapter XI). The latter may conveniently be referred to as martensitic in structure, because its origin appears to be analogous to that of the true iron-carbon martensite in artificial irons.

Needles of martensite are reported by Vogel (1927) in certain meteoric irons, attributed by him to local carbon enrichment, but the author considers them to be the iron-nickel transformation structure referred to.

Troostite; sorbite.—With slower cooling, but still too fast to permit formation of normal pearlite, a black structure is produced which is unresolved at 1,000 diameters but at very high magnification is shown to be actually pearlite in a very fine dispersion (pl. C). This has been called troostite, but by the more recent writers it is designated as fine pearlite. In artificial irons it occurs in irregular nodular forms with an obscure radiating structure. Minute inclusions of similar appearance observed in some meteoric irons have been identified with troostite, but the author is of the opinion that they are not an iron-carbon but an iron-nickel structure produced in a somewhat analogous manner.

Troostite forms at around 550° to 600°. With still slower cooling, at a temperature approaching that at which normal pearlite is formed a similar black component is produced, appearing at moderate magnification to have an obscure granular or amorphous structure. At higher magnification its structure is more or less lamellar. This was formerly designated as sorbite, but in reality it is a refined pearlite.

The terms troostite and sorbite are falling into disuse, both being referred to as pearlite. The terms pearlitic and sorbitic, however, will be used in this work as convenient designations for structures having the appearance either of lamellae or of a black unresolved aggregate. The latter structures, composed of particles of gamma and alpha nickel-iron, the author believes may sometimes have been mistaken for the true iron-carbon troostite or sorbite.

Pearlite in meteorites.—True pearlite has not been found in meteoric irons, although some contain enough carbon to make a local development of pearlite theoretically possible. A perfect pearlitic pattern of high- and low-nickel lamellae, however, was observed by Pfann (1917) in San Cristobal, a very high nickel iron, and also by the author in Otumpa (H), Seeläsgen (Ogg), Leeds (Om), Youndegin (Og), and Walker County (H), examples of which are illustrated in the plates.

Such structures, however, are not strictly eutectoids, made up, like pearlite, of components of definite compositions, but merely two-phase gamma-alpha structures in which the composition of at least one phase is variable.

VIII. THE IRON-NICKEL SYSTEM

When nickel is substituted for carbon the resulting diagram is quite different from that of the iron-carbon system, yet with interesting and important analogies.

Differences in transformation.—The phase changes and the general processes of transformation are similar; but instead of a separation of ferrite and cementite there is a separation of a body-centered alpha phase (kamacite) from a face-centered gamma phase (taenite). And just as a ferrite-cementite eutectoid is produced with 0.80 percent of carbon, so with high (but indefinite) percentages of nickel we find structures somewhat suggesting in appearance a taenite-kamacite eutectoid; in the absence of any accepted designation for such structures they will be referred to as paraeutectoid.

It is clearly to be noted that the heterogeneous structure of meteoric irons is not due to the segregation of iron and nickel, but to the segregation of the nickel-richer and nickel-poorer solid solutions of iron and nickel—taenite and kamacite—just as the structures of steel are produced by the segregation of cementite and iron, not of carbon and iron.

Whereas the saturation of cementite in iron occurs at a point corresponding with about 0.01 percent carbon, the saturation of taenite in kamacite at room temperature is at a point corresponding with about 6 percent nickel. Therefore a meteoric iron with less than 6 percent nickel (kamacite) is a homogeneous solid solution analogous to an artificial iron containing less than 0.01 percent of carbon and, like it, is structureless except for granulation.

Early iron-nickel diagrams.—The equilibrium diagram of the iron-nickel system has been a subject for conflicting views, and even now it is not free from doubt.

The origin of a two-phase iron-nickel structure by transformation in the solid state was first made clear in the classic diagram of Osmond and Cartaud (1904), modified by Osmond and Roozeboom in 1911. The diagram is shown in simplified form in figure 4, embodying the temperatures of the earlier diagram and the nickel percentages of the later one. Comparing this diagram with the iron-carbon diagram, we may note that the line AC, marking the beginning of the gamma-alpha transformation, is much lower and ends at about 350° instead of 723.°

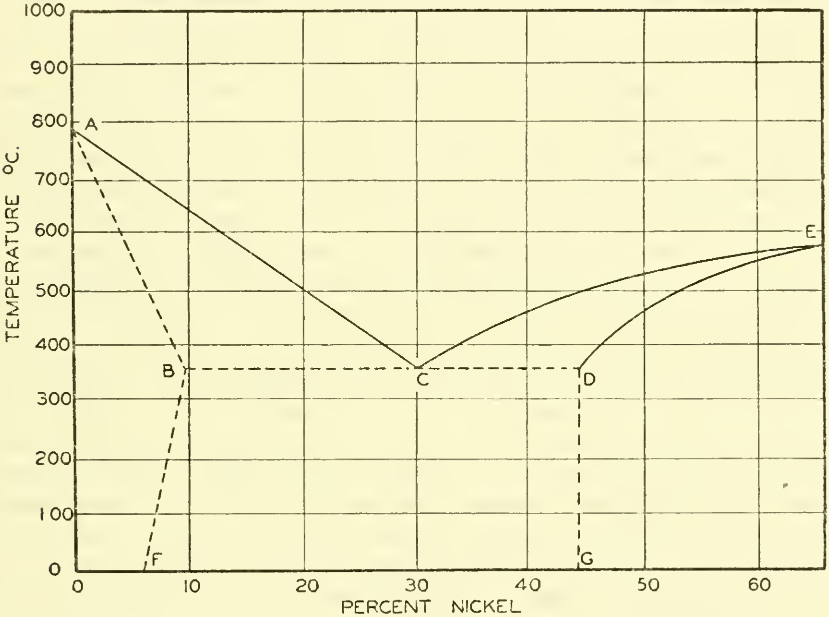

FIGURE 4.—Early iron-nickel diagram.

An alloy with 5 percent nickel in cooling would enter the gamma-alpha range at a little above 700° and the alpha phase would begin to separate from the gamma phase, producing a heterogeneous structure. Gamma would first predominate, the proportion of alpha increasing until from about 450° downward, the mass would be wholly in the alpha phase. A meteorite of that composition would be a hexahedrite (or a nickel-poor ataxite), consisting wholly of alpha kamacite.

With a nickel content above 6 percent the structure would remain heterogeneous at room temperature, the iron being an octahedrite or (with nickel above about 13 percent) a nickel-rich ataxite.

The supposed eutectoid.—Osmond and Cartaud assumed a eutectoid line BD at about 350°, corresponding with the combined A_3—A_1 line FG at 723° in the iron-carbon diagram, and they assumed also that the line CE was a phase transformation line. Both assumptions are now generally considered as erroneous, as there is believed to be no iron-nickel eutectoid, and the line CE marks only the beginning of ferromagnetism in cooling, and not a phase change.

The views of Osmond and Cartaud, supported by Benedicks and later by the Hansons and other authorities, were substantially embodied in the diagram of Guertler (1910) for meteoric irons. Pfann (1917), accepting it with slight modifications, fixed the eutectoid ratio of nickel around 17 to 18 percent, at which composition a meteoric iron actually is an ataxite with a paraeutectoid structure.

In accordance with the Guertler diagram, he held, quite correctly, that an iron with less than 6 percent nickel would be a hexahedrite consisting wholly of kamacite, and from 7 to 13 percent it would be an octahedrite, with the amount of plessite (the assumed eutectoid) increasing. With more than 13 percent it would consist of plessite with vestiges of kamacite; at 17 to 18 percent of eutectoid (paraeutectoid) plessite; then taenite would increase and plessite diminish, until at about 27 percent it would be pure taenite. Such, in fact, are substantially the changes that are observed with rising nickel content; examples of the various types will be found in the plates.

The writers supporting that theory have differed somewhat as to the eutectoid percentage. The Hansons give the composition range for all structures between pure kamacite and pure taenite as 9 to 30 percent, as compared with Pfann's 7 to 27 percent. They place the eutectoid temperature at about the same point as did Osmond and Cartaud.

Eutectoid theory untenable.—The earlier theory of the iron-nickel system has been outlined at some length because of its historical interest and the distinguished authorities that have supported it. That support has continued almost, if not quite, to the present; for the diagram presented as recently as 1927 in International Critical Tables retains the eutectoid line, and an analogous line is seen in the still more recent diagram of Bradley and Goldschmidt (1939) referred to later.

The eutectoid theory seems so consistent, and fits so well the known structures of meteoric irons, that one abandons it with some reluctance. It seems to the author, however, to be untenable.

Apart from the original erroneous assumption that the magnetic transformation line in the diagram marks a phase change, the existence of a definite intermetallic compound was assumed. In pearlite, which is a true eutectoid, the two components—ferrite and cementite—have definite and constant compositions; and if an iron-nickel eutectoid, the counterpart of pearlite, existed in meteoric iron its two components, kamacite and taenite, likewise should have definite compositions. Various writers have believed that taenite is such a compound, its hypothetical composition being placed oftenest at Fe_2Ni. As will presently be explained, however, taenite has no definite composition, and the prevailing view is that there is no intermetallic compound of iron and nickel.

The composition of taenite.—As noted earlier (Chapter III) the nickel content of taenite has been fixed by various analysts at percentages from 13 to 48, and recently Smith and Young (1939) by thermomagnetic analysis found taenite in Butler to contain about 50 percent nickel, and in the narrowest lamellae as much as 55 percent.

The impossibility of isolating "pure" taenite was a bar to the efforts of the earlier analysts; but San Cristobal presented an exceptional case that seemed to obviate that difficulty. Inasmuch as the taenite in that iron is apparently a clear segregate and easily isolated, Pfann considered it an example of substantially pure taenite. He found its composition to be 26.25 to 26.45 percent nickel, and he therefore placed the saturation point of kamacite with respect to taenite at 27 percent. The author, however, found the taenite in San Cristobal to contain a profusion of kamacite particles, as well as areas of a gamma-alpha aggregate and sorbitic patterns (pl. 28), which indicate incomplete separation of the alpha from the gamma phase; therefore the nickel content of the taenite itself must be somewhat higher than the above percentages. It should be regarded as further increased by the presence of cobalt, of which San Cristobal contains at least 1 percent and which in this connection may be considered identical with nickel.

Mehl and Derge (1937) found that only in artificial alloys with less than 28.5 percent nickel could a pure gamma structure be retained by quenching, and that at 27 to 28 percent the transformation was only partial. This would be consistent with the structure of San Cristobal. At 34 percent they found no transformation possible, which is consistent with the structure of Santa Catharina (Ni-Co 35.47 percent). Smith and Young (1939) and Bradley (1939) hold that typical meteoritic structures represent an equilibrium between low and high nickel phases, the former kamacite with 6 percent, the latter taenite with 26 to 30 percent nickel.

The nickel-rich phase, corresponding with taenite, in the diagram in International Critical Tables (1927), indicates a percentage of 34.5, corresponding with the formula Fe_2Ni. That point also has been found to be marked by a change in dilatation curves, which tends to support the views of those who have favored the theory of an iron-nickel intermetallic compound of definite composition.

The foregoing views are cited to show that arguments still can be adduced in support of the assumption of the existence of an intermetallic iron-nickel compound as one of the components of the paraeutectoid. But with full deference to these authorities, the prevailing view now seems to be that there is no such compound but that in an alpha-gamma equilibrium structure the gamma phase is variable in composition, depending upon the stage of the transformation. Thus whether taenite contains 13 or 55 percent nickel (the extremes found by analysts) depends upon the temperature at which it segregates and the rapidity of cooling. Therefore an ataxite having the appearance of a true eutectoid of very fine and regular pattern (e. g., Ternera, Linville, Morradal) is, after all, merely a two-phase structure in which certainly the gamma component has no fixed composition.

An eclectic iron-nickel diagram.—In figure 5 an artificial iron-nickel diagram is presented that, in the author's opinion, harmonizes to a fair degree the more recently accepted views of metallographers. It resembles the diagram presented by Marsh (1938, p. 53) as summarizing the data of eight or nine recent investigators.

The line AC, below about 500°, might well be dotted to indicate that it is conjectural rather than exact; for the authorities are not yet in agreement. Thus the recent diagrams of Owen and Sully (1939) and of Bradley and Goldschmidt (1939) differ in important respects from the diagram here presented.

It is to be emphasized that this diagram, although reflecting the prevailing views, is inconsistent with the transformation of meteoric iron. Thus, according to the diagram, kamacite might contain 10 or even 15 percent of nickel, whereas it actually contains not more than about 6 percent.

In the early diagrams the line AC drops almost vertically from a point corresponding with 400° or 500° and less than 10 percent of nickel, and in the diagram of Owen and Sully it drops from a point corresponding with about 400° and 6 percent, approximately the point E in figure 5. The diagram would be more nearly applicable to meteoric iron if so drawn; for with less than about 6 percent nickel it is homogeneous alpha (kamacite), whereas at all higher percentages it shows a two-phase structure of alpha and gamma (taenite).

Because of the marked hysteresis or lag in the transformation of iron-nickel alloys, there is a considerable thermal range between the beginning and the end of transformation, either in heating or cooling. (See figure 6.) It is therefore impossible to determine the actual equilibrium temperature line for iron-nickel alloys. It is possible in iron-carbon alloys, in which hysteresis is slight and the gap is practically negligible. Figure 5 indicates the range of transformation in cooling. As shown in figure 6, transformation in heating begins and ends at higher temperatures.

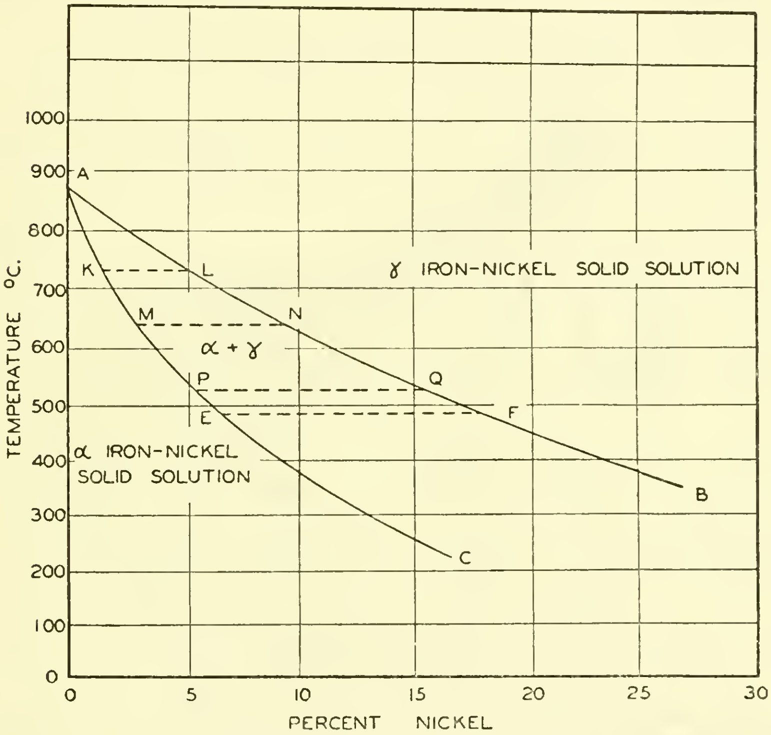

Figure 5.—Eclectic iron-nickel diagram.

Comparisons with the iron-carbon diagram.—Comparing this diagram with that of the iron-carbon system, several differences are apparent of which the most striking are these:

1. Whereas the iron-carbon system ends at 9.60 percent carbon, that being its saturation point in melted iron, the iron-nickel diagram (if presented fully) would extend to 100 percent nickel, there being no saturation point for nickel in iron.

2. The structural changes, which in artificial irons are confined to a very limited range of carbon content, extend from 6 to 30 percent nickel.

3. The line AB, marking the beginning of the gamma-alpha inversion, is greatly depressed.

4. The line AC is still more depressed, thus leaving a much wider gap than in the iron-carbon diagram.

The lines A_1 and A_3 in the iron-carbon diagram do not appear in the iron-nickel diagram, which shows only the beginning and the end of the gamma-alpha transformation.

Hysteresis increased.—In pure iron the critical points mark practically definite temperatures; but in alloys there is a more or less pronounced lag (hysteresis) in the transformation, which takes place somewhat above the normal points on heating and somewhat below them on cooling.

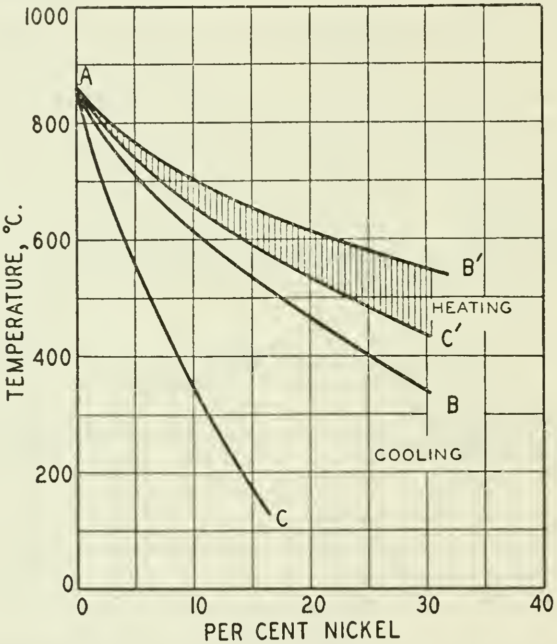

Figure 6.—Iron-nickel constitution diagram.

Hysteresis is comparatively small in the iron-carbon system, but is greatly increased by the presence of nickel. In an iron-nickel alloy it becomes very pronounced, as shown in figure 6, which indicates relative positions of the gamma-alpha range on heating and on cooling. The lines AB and AC mark the beginning and the end of the gamma-alpha transformation on cooling, the shaded area marking the position of the corresponding range on heating.

This fact has a bearing on the modification of meteoric structures by reheating. With an octahedrite containing 7 percent nickel, for example, the gamma-alpha transformation begins at about 700° and is completed at about 500° (fig. 5). But in reheating (fig. 6) the alpha-gamma transformation does not begin at the line AC, or even at the line AB. The temperature must reach the line AC′, about 700°, before any change in the established structure would begin to take place. Then in recooling the iron would again have the same long sojourn in the gamma-alpha range, during which its former structure might be reestablished.

A meteoric iron-nickel diagram.—The diagram shown in figure 5 relates to artificial iron-nickel alloys, embodying approximately the results of experimentation. If a diagram could be accurately drawn for meteoric iron it probably would show considerable variation in the position of the transformation points, although the nature of the transformations would be similar to those in artificial iron-nickel alloys. Unfortunately the construction of such a diagram is impossible because of our limited knowledge of conditions of production of meteoric irons and the thermal changes to which they have been subjected.

In the artificial iron-nickel diagram the transformation points are determined positively from the behavior of alloys of definite composition under controlled conditions; but in meteoric iron only the final cooled product can be studied, and the transformation points can merely be inferred from the observations of various investigators upon irons of varying compositions.

One sample, for instance, may contain a substantial proportion of phosphorus, which depresses the gamma-alpha transformation, while another may be phosphorus-free. The rate of cooling also markedly affects the position of the transformation, which is depressed as the rapidity of cooling increases, and it is impossible to allow for that factor. Meteoritic structures generally were produced by extremely slow cooling, which would make the transformation take place at higher temperatures than in artificial iron-carbon alloys.

It is believed that the diagram as presented approximates in some degree the equilibrium conditions of iron and nickel in meteorites. We may fairly assume, however, that in meteoric irons both lines are less depressed than in artificial alloys, so the corresponding structural changes would take place with higher percentages of nickel than in artificial alloys; or conversely, that with the same percentage of nickel they would take place at higher temperatures because of much slower cooling than is possible to attain artificially. Cooling of secular slowness might produce a more perfect transformation at lower temperatures than could be accomplished in a laboratory.

It may well be that, for meteoric nickel-iron, the line AC in figure

5 should drop vertically from a point corresponding with about 6 percent nickel. It is approximately so drawn in the early diagram of Osmond and Cartaud (fig. 4), and it was accepted by Guertler and other older authorities. It also appears, at a somewhat higher percentage, in the recent diagram of Bradley and Goldschmidt (fig. 7), which is presently discussed.

The effect of cobalt on the transformation of iron is virtually identical with that of nickel, so the iron-nickel system may be assumed for practical purposes to be an iron-nickel-cobalt system. Therefore the cobalt content of a meteoric iron should always be considered in connection with its transformations, and an iron containing 14 percent of nickel and 1 percent of cobalt may be judged in the same way as if it contained 15 percent of nickel.

Bradley and Goldschmidt's diagram.—Yet another iron-nickel diagram should be noted—that offered by Bradley and Goldschmidt (1939) as the result of annealing experiments and of X-ray powder photograms of natural and artificial iron-nickel alloys. The diagram is shown in figure 7.

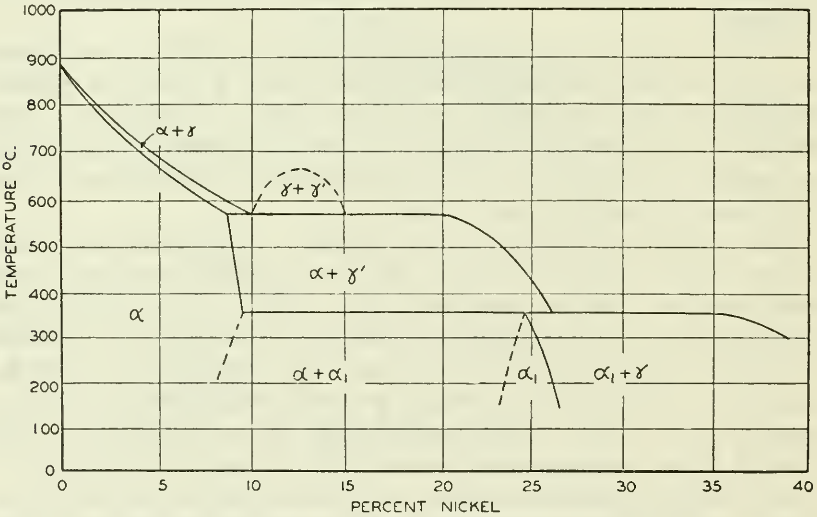

Figure 7.—Bradley and Goldschmidt's iron-nickel diagram.

Affirming the conclusion of Owen and Williams (1938) that octahedral structures in meteorites represent a kamacite-taenite equilibrium between 350° and 580°, they assert that a further transformation occurs along a line drawn at 350°, which coincides with the eutectoid line in the earlier diagrams of Osmond and Cartaud, Bendicks, and the Hansons.

The very narrow gamma-alpha range between 0 percent and about 9 percent nickel in their diagram is open to question as applied to meteoric irons. Thus, a medium or fine octahedrite with 7 or 8 percent of nickel could have developed its elaborate structure within a range of only about 30° around 600° and must have retained it intact while cooling from 600° to 500°, within which range there still is considerable atomic mobility and therefore more or less active diffusion. Such conditions of production are not indicated by the observed structures.

Below 350° the diagram indicates a gamma phase (taenite) with about 35 percent nickel, and at about 25 percent an ordered gamma-alpha structure designated as α_1, corresponding with the eutectoid ratio assumed by the earlier diagrams of Pfann and others. From 10 to 25 percent there is alpha (kamacite) with increasing proportions of α_1; above 25 percent α_1 with increasing gamma.

IX. METEORIC NICKEL-IRON

Although the structures of meteoric irons show variations due to the presence of other substances (especially phosphorus), the iron-nickel diagram is the basis for their study and interpretation. An artificial iron-nickel alloy is commonly homogeneous, regardless of composition or temperature. In the natural alloy, however, a strongly marked heterogeneous structure may develop, caused by the separation of one phase from another during transformation—an alpha nickel-poor phase (kamacite) and a gamma nickel-rich phase (taenite).

Structural changes.—The structures resulting from the phase changes parallel in a degree those in the artificial iron-carbon alloy.

A. When nickel is below 6 percent (corresponding with the saturation point of taenite with respect to kamacite) the final product is a homogeneous solid solution corresponding with the solid solution of cementite in ferrite when the percentage of carbon is below 0.01 percent. This is kamacite, the substance of hexahedrites.

Assuming the nickel content to be 5 percent, the alloy cooling through the gamma range, the gamma-alpha transformation will begin at the point L (fig. 5). The transformation consists of the separation of the two phases—a nickel-rich gamma of the composition L, and a nickel-poor (alpha) of the composition K—starting the formation of the Widmanstätten structure. The separation takes place along octahedral planes.

As transformation proceeds the nickel-rich and nickel-poor phases must remain in equilibrium; therefore their respective compositions change to M and N, and finally to P and Q at around 550° where the transformation is completed, the alloy now consisting wholly of alpha kamacite. This corresponds with the solid solution of cementite in ferrite when the percentage of carbon is below 0.01

percent. For a time the iron had an octahedral structure, while it was within the gamma-alpha range. But this condition was transitory, disappearing when cooling reached about 550°, when the transformation is completed and the iron is wholly alpha.

B. The saturation ratio of taenite with respect to kamacite is reached with about 6 percent nickel. This can be regarded as the saturation ratio at room temperature; for at about 450° the metal has become so rigid that diffusion virtually ceases and the structure remains unchanged with further cooling. So when the nickel content is above 6 percent, whatever Widmanstätten structure existed at around 450° is preserved. If it only slightly exceeds 6 percent there are only slight traces of the structure—in other words, a coarsest octahedrite, which sometimes may be barely distinguishable from hexahedrites. It may show no segregation of taenite, consisting entirely of wide, more or less indistinct, kamacite bands.

C. As nickel increases from 6 percent to around 11 or 12 percent, with the lines AB and AC steadily lowering, the proportion of kamacite decreases while that of taenite rises. Kamacite bands grow narrower and clearer and are separated more and more widely by plessite fields. This structure corresponds with that of a hypoeutectoid steel in which ferrite predominates. The octahedral structure passes from medium, through fine, to finest, in which the very narrow kamacite bands appear only sparingly in a groundmass of plessite; this structure corresponds with that of a hypereutectoid steel. At around 13 percent nickel (e. g., Cowra) continuous bands give place to a dispersion of minute spindles or rounded particles of kamacite, like the remnants of ferrite in a steel that approaches eutectoid composition. At around 14 percent kamacite has disappeared, except for scattered particles, the iron now being an ataxite.

D. At about 17 percent nickel, the hypothetical eutectoid ratio of kamacite and taenite, there is a uniform two-phase structure approaching a eutectoid in character. The iron is now a dense, or paraeutectoid, ataxite—a uniform distribution of kamacite and taenite particles, the taenite predominating. The structure is identical with some forms of dense plessite, and corresponds with pearlite or eutectoid steel in the iron-carbon series. It is not, however, a true eutectoid in which the components have definite compositions, but only a structure of two phases of variable compositions. Vestigial kamacite in the form of scattered particles is still found.

E. As the nickel content further rises, the increasing taenite becomes still more predominent—an imperfectly transformed groundmass with an acicular or indistinct structure—and at around 26 to 29 percent the iron consists partly of the same groundmass and partly of taenite.

F. At somewhat more than 30 percent nickel the iron becomes wholly taenite, the only example being Santa Catharina, with 34.37 percent nickel (35.87 percent Ni-Co). This, the homogeneous unsaturated solution of kamacite with respect to taenite, is the counterpart of A, which is the homogeneous unsaturated solution of taenite with respect to kamacite. The two states are not infrequently referred to respectively as unsaturated solutions of kamacite in taenite, and of taenite in kamacite, which is a convenient description although it represents a reversal of the actual mechanism.

G. From this point onward the alloy is taenite with a rising nickel content—that is, an increasingly nickel-rich gamma phase—passing finally (in theory) into pure nickel. Actually no meteoric iron is known with more than 62 percent nickel, the content of Octibbeha. This iron is wholly in the gamma phase, as is shown by the characteristic twinning of its grains (pl. 34).

The trias summarized.—The foregoing outline traces the changes that produce the three members of the "trias"—kamacite, plessite, and taenite—substantially as stated by Pfann (1917) who summarized their occurrence as follows:

Kamacite: As (*a*) the sole component of irons with less than 6 percent nickel (hexahedrities); (*b*) as a segregate with octahedral orientation, forming the Widmanstätten structure in irons with more than about 6 percent nickel; (*c*) as a second segregate in the coarse or light plessite fields in octahedral irons; and (*d*) intimately mingled with taenite as a component of dense or eutectoid (paraeutectoid) plessite.

Taenite: As (*a*) the sole component in irons with more than 27 percent nickel; (*b*) as a segregate in irons with 18 to 27 percent nickel; (*c*) as lamellae bounding the kamacite bands in the Widmanstätten structure; and (*d*) as a component of eutectoid (paraeutectoid) plessite, associated with the fourth form of kamacite.

Plessite: As (*a*) noneutectoid fields with coarse structure in octahedral irons; (*b*) as eutectoid (paraeutectoid) plessite, more or less perfectly developed, in plessite-rich octahedrites and nickel-rich ataxites.

There are differences of opinion as to the formation of the Widmanstätten structure, which is discussed in Chapter XI. The foregoing, however, seems to the author a satisfactory summary of the essential mechanism.

The demarcation in classifying the different types of structure is not definite. Thus there is a narrow "twilight zone" between hexahedrites and octahedrites, and a wider one between octahedrites and ataxites.

An attempt has been made to indicate the composition ranges of these structures, in connection with the iron-nickel diagram, in figure 8.

Ataxites are designated as nickel-rich to distinguish them from certain low-nickel irons, usually hexahedrites, that have lost their normal structure through reheating and which are designated as nickel-poor ataxites. Such a structure is secondary and not a product of the orderly transformations that have been discussed.

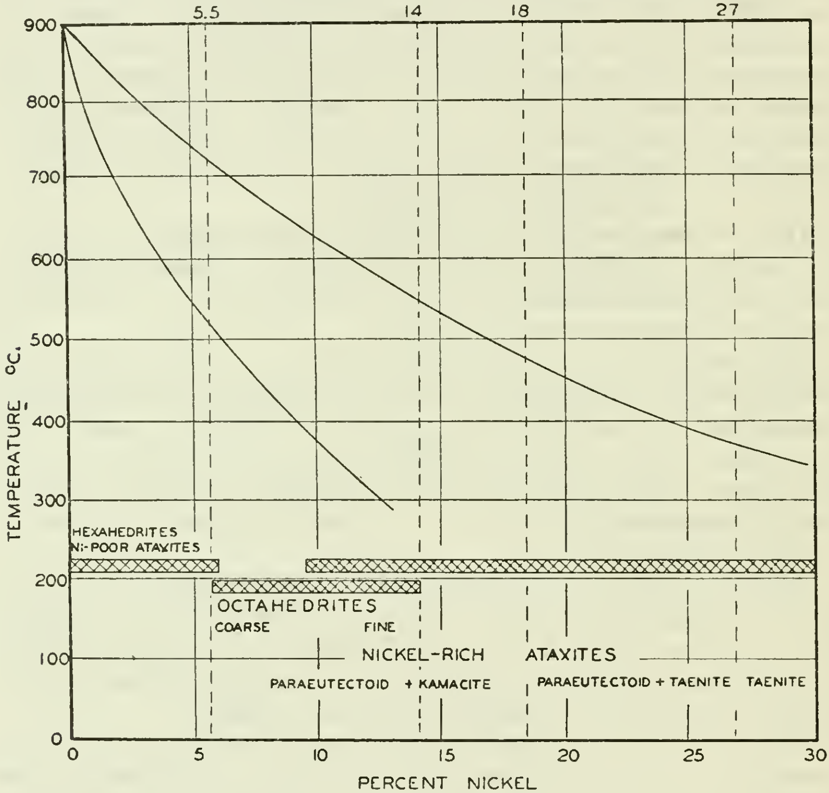

Figure 8.—Composition ranges of meteoric irons.

Crystallization in meteorites.—The crystallization of artificial irons begins with the formation of dendrites from the melt, which change into grains of body-centered delta iron. As atomic mobility is great, the grains are large. In the gamma phase the grains become face-centered and on further cooling transform into body-centered alpha iron. This change is accompanied by recrystallization, the result being an aggregate of grains that may be similar in size to the earlier gamma grains, or smaller, depending upon the conditions of cooling. The final product is an aggregate of grains (crystallites), but not always uniformly oriented.

Iron meteorites are generally regarded as single or unigrain crystals, their structure running uninterruptedly throughout the mass. This may be due to one of two mechanisms. The liquid metal may have frozen with such extreme slowness that the whole mass crystallized upon one nucleus, producing a single crystal; or if the mass in the gamma range was an aggregate of grains, with cooling of secular slowless, the aggregate may have changed to a single crystal by simple grain growth—smaller grains merging into larger ones until finally only one was left.

The unigrain character is shown in "normal" hexahedrites, which have a distinct cubic cleavage. In granular hexahedrites, the planes may be diversely oriented in different grains and the cleavage is interrupted. In octahedrites the unigrain character is reflected in the continuity of the octahedral pattern, which normally runs through the entire mass without change of directions.

Octahedrites, however, although they are practically unigrain in character, are nevertheless not single octahedral crystals. Slow cooling in the gamma-alpha range produced an apparent unigrain octahedral structure in the Widmanstätten pattern. The kamacite of the bands, however, in body-centered alpha, the taenite lamellae remaining face-centered gamma, so that the Widmanstätten structure is only a remnant pattern or pseudomorph of a former octahedral crystallization. Thus an octahedrite, though showing an apparent unigrain character, has neither cubic nor octahedral cleavage—the normal cubic cleavage of its kamacite being suppressed by the interference of the octahedrally arranged taenite lamellae, and probably also in many cases by the acicular transformation structure often found in the kamacite itself (see Chapter XI).

Exceptionally an apparent, though false, octahedral cleavage may result from mechanical separation along the planes of the bands because of the invasion of oxide. In the unique case of Horse Creek such a cleavage is caused by lamellae of phosphide, but is not on octahedral planes (see pls. 60, 61).

The dendrites referred to, marking the first stage of crystallization from the melt, may be preserved in artificial irons by quick cooling. Their outlines also may be preserved by the segregation of impurities even after the dendrites themselves have been wholly changed by granulation. In meteoric iron dendrites apparently do not exist except in rare instances as a result of a slight superficial invasion of melted oxide during atmospheric flight (see Chapter XIII). In two instances the author observed a dendritic structure in inclusions containing an iron-carbon-phosphide eutectic (pls. 65, 66).

Granulation.—Kamacite may be homogeneous, as in many hexahedrites and in the bands of many octahedrites, or it may be granular, the grains ranging from very minute to macroscopic. Such grains may be a primary structure, or a secondary structure caused by reheating.

As already stated, the large grains first formed from the melt in artificial iron change to smaller grains in the upper gamma range and disappear, although their original outlines may remain visible because of the presence of impurities along the former larger grain boundaries.

In meteoric irons their preservation in that manner is common. In some of the very coarsely granular (inaptly termed brecciated) hexahedrites a polished surface shows grains with dimensions up to 2 or 3 inches. Such grains usually have diverse systems of Neumann lines and are bounded by a dark substance. On weathering such irons are likely to break up into rounded nodules.

Smaller grains, but still of macrosize, are observable in numerous hexahedrites, coarse octahedrites, and nickel-poor ataxites. The boundaries of grains, preserved from the high gamma range, are sometimes marked by copious precipitation of phosphide, which could have taken place only at a high temperature. In Soper (pl. 11) this is especially prominent.

Within large grains a finer granulation may be observed, caused by the normal breaking up of the original large gamma grains whose former outlines remain, or by the recrystallization accompanying the gamma-alpha transformation. A uniform structure of macroscopic grains is found in some ataxites (e.g., Mejillones) their diverse orientation giving them the appearance of a mass of glistening flakes with macroetching.

Granulation is usually coarsest and most conspicuous in the low-nickel irons, where the gamma-alpha range was narrow at a high temperature, and therefore the Widmanstätten structure was transitory and relatively slight, there being little difference between the higher and lower nickel phases (see fig. 5). In octahedrites a stronger Widmanstätten pattern, the production of which continued through a longer and lower temperature range, often obscures the grains; although they are well marked in many coarse and medium octahedrites. Numerous examples are illustrated in the plates.

In nickel-rich ataxites the grains usually are obliterated, although the outlines of large gamma grains may sometimes be traced in a dense paraeutectoid groundmass (e.g., Illinois Gulch, pl. 21).

In hexahedrites the complete transformation of the gamma iron into a unigrain mass of kamacite is shown where Neumann lines pass without change of direction through the outlines of the original large gamma grains.

The large grain boundaries do not penetrate plessite fields, though the latter may show their own grain boundaries. They also do not cross the taenite lamellae separating kamacite bands.

In the neighborhood of schreibersite inclusions granulation is usually finer (e.g., Mejillones, pl. 11). In artificial irons phosphorus inhibits grain growth.

Alpha granulation.—On the analogy of artificial ferrite, there should be no separate alpha granulation, so it may be assumed that all primary granulation in meteoric irons originated before the gamma-alpha transformation.

In ferrite there is often a faint reticulation within the ordinary grains, which is called alpha veining and has been explained in various ways. The author has observed no clear example of alpha veining in kamacite. In a few instances there is an appearance suggesting it, but the appearance of lines in such cases is probably due to minute particles of impurity along the outlines of obliterated gamma grains.

Smithland, a nickel-rich ataxite, shows a phantom grain pattern due to the suppression of the paraeutectoid structure along former grain boundaries (pl. 26).

Secondary granulation, a result of re-reheating into the gamma-alpha range or into the lower gamma range, is found in nickel-poor ataxites and also in zones of alteration near the surface of octahedrites and hexahedrites (see Chapter XIII). Such granulation is fine and irregular.

The twinning structure in gamma grains is discussed in Chapter XI.

Composition of kamacite.—The composition of kamacite, as chemically determined, has already been referred to in Chapter III. As the saturation ratio of nickel in iron is about 6 percent, this is the maximum nickel content of kamacite. Thus the upper limit of its nickel content is definite. Below that point, however, it is indefinite because any iron with less than 6 percent nickel would necessarily be in the alpha phase at room temperature and therefore would be kamacite.

The best analyses of hexahedrites, which consist of kamacite, actually show on the average about 5.5 percent nickel, with a very few slightly less than 5 percent. Fractional percentages of cobalt also are always present, and the combined nickel-cobalt percentages vary from about 6 to 6.5 percent.

As nickel and cobalt are practically identical in their effects upon the phase transformations, they may be considered as a unit metallographically. Rinne and Boeke (1907) fixed the saturation point of nickel and cobalt in iron as about 6 percent, which is fairly consistent with the average nickel-cobalt percentages found in the analyses of hexahedrites. This may be taken as a fair approximation of the maximum of the two in kamacite. Theoretically there would seem to be no reason why that content might not sometimes be much lower; but as previously observed, no recent analysis of any meteoric iron, to the author's knowledge, shows less than about 5 percent nickel, and only two show slightly less than 6 percent of nickel and cobalt. Old analyses showing less than 4 percent nickel cannot be accepted unreservedly.

X. HEXAHEDRAL STRUCTURES

As is apparent from the diagram, the simplest structure of meteoric iron is that of hexahedrites, which contain less than 6 percent of nickel and therefore consist wholly of alpha kamacite. The heterogeneous gamma-alpha stage (AEF in fig. 5) was transitory, and before diffusion was stopped by cooling the alpha phase was established. As a result the structure of such irons is simple, lacking the varied and interesting features in octahedrites and ataxites that were produced during transformation.

Classification.—Hexahedrites are classified as normal and granular (also less aptly termed brecciated).

A normal hexahedrite consists of homogeneous kamacite. A macroetched surface shows no structure except for Neumann lines and occasional visible inclusions. Under the microscope a typical field shows only clear kamacite, usually marked by Neumann lines and often strewn thickly with rhabdites or phosphide particles. Remnant grain boundaries may be visible, but they are usually faint. An outstanding characteristic of normal hexahedrites is a cubic cleavage, which is often observable on a broken surface, due to the cubic crystallization of the alpha phase.

Granular hexahedrites are characterized by visible macrograins, often of large size. When grain boundaries are not strongly marked, the coarse granulation may still be recognized on a polished surface because of the varying orientation of Neumann lines in the grains. In some hexahedral irons (e. g., Central Missouri, New Baltimore) the grains may reach dimensions of several inches, the boundaries strongly marked by the deposition of impurities. Each grain is a unit, typically hexahedral in structure, with its own crystallographic planes.

Inclusions.—Hexahedrites as a class are rich in nonmetallic inclusions—schreibersite, troilite, less frequently graphite, and daubréelite.

The phosphide appears as schreibersite bodies, often numerous and sometimes reaching dimensions of inches. They are of varied irregular shape, often sprangling or meandering, sometimes in clear-cut graphic forms. It also occurs as needles (lamellae) of various dimensions. These are sometimes parallel and oriented; sometimes strewn irregularly in parallel bands; sometimes in radiating groups. Exceptionally such needles are very long and extremely fine.

Phosphide in the form of rhabdites is almost always present, sometimes sparse and again very abundant. The same is true of minute phosphide particles, which often are very thickly disseminated, appearing as minute black dots because of the strong etching attack along their interfaces. Where there is an inclusion or large needle of schreibersite, the immediate vicinity is usually free from phosphide particles and rhabdites, the phosphide content in the adjacent iron having concentrated in the larger body.

Troilite is abundant in hexahedrites, usually in nodules sometimes an inch or more in diameter. It also occurs as smaller rounded or elongated inclusions and in rare instances as hexagonal crystals.

Daubréelite is much more common in hexahedrites than in other irons. It is usually adjacent to troilite, or intergrown with it, not infrequently in a banded pattern.

Graphite occurs as nodules, sometimes of large size, and is often associated with troilite inclusions, enveloping them or penetrating them.

Examples of the various inclusions are shown in the plates.

Neumann lines.—In most hexahedrites Neumann lines are visible to the eye on a macroetched surface and often are very profuse, two or more sets being discernible. Sometimes, however, they appear so sparingly or indistinctly as not to be readily visible. It is possible that they may be absent in some cases, although the author has not observed a hexahedral iron in which they could not be found in some small degree.

In normal hexahedrites, which are unigrain crystals, the lines may run unbroken across the entire section. In granular hexahedrites each grain has its own system, although the direction of the lines may be parallel or nearly so in a number of adjacent grains. In hexahedrites that are not granular but that still show more or less distinct outlines of former gamma grains (remaining visible because of impurities along their boundaries) the Neumann lines are apt to run uninterruptedly across such remnant boundaries.

The nature and origin of Neumann lines, and the effect of thermal changes upon them, are discussed in Chapter XVI.

Sets of closely packed Neumann lines may give the semblance of a sheen, varying with the direction of the light, but the kamacite itself has a true sheen which is independent of the presence of the lines; see Chapter III.

Taenite and plessite.—Inasmuch as the percentage of nickel is below the saturation point, taenite should not be rejected in hexahedrites; and it has been assumed that taenite (and therefore plessite) is not and could not be present. The author, however, has observed at least two hexahedrites with plessite fields in which taenite was clearly developed (Otumpa, Sierra Gorda, pls. 44, 46, 78). In both these irons the Ni-Co content is even below the average of hexahedrites, it being, respectively, 5.68 and 5.83 percent.

The existence of such fields might be explained by rapid cooling from a relatively high range. The separation of gamma and alpha in such a range, in an iron of such low nickel content, would normally be transitory and the taenite would disappear as the mass became wholly alpha. With quick cooling, however, the mass might have become rigid so rapidly that some of the taenite would be preserved. In Sierra Gorda the structure was not visible with light etching, indicating little difference in the solubility of the taenite and kamacite. This would naturally be the case if the taenite was a product of a normally transitory separation at a high temperature.

These instances are altogether exceptional. In a typical hexahedrite, well below the borderline of nickel content for such irons, it may be assumed that there is no segregation of taenite, and therefore no plessite.

Transitional types.—With a rising nickel content hexahedrites graduate into coarsest octahedrites. In such transitional types traces of the octahedral pattern may be discernible in one place and only a uniform hexahedral structure in another part. Even after the banded pattern is clearly established no taenite may be present, the bands not being separated by visible taenite lamellae (e.g., Osseo). It may be in such cases that there are invisible incipient segregations of taenite between the bands.

Hexahedrites may be altered by heat into nickel-poor ataxites, as described in Chapter XIII. Here again there are transitional forms which might be assigned to either class.

A number of all-kamacite irons with very large grains, more or less suggesting a banded arrangement, are classed by some writers as hexahedrites and by others as coarsest octahedrites. Examples of such irons are discussed in Chapter II.

XI. OCTAHEDRAL STRUCTURES

Octahedrites have a macroscopic structure consisting of intersecting bands corresponding with the planes of the gamma phase, to which the name Widmanstätten structure was given in honor of Alois Widmanstätten of Vienna who discovered it in 1808, first by heat tinting and later by etching. It begins with about 6 percent nickel and disappears in the neighborhood of 13 percent.

Genesis of the Widmanstätten structure.—A nickel-iron alloy with less than 6 percent nickel is in the alpha phase at room temperature. Therefore, hexahedrites, which contain an average of about 5.5

percent nickel, show no structure due to phase changes. At higher temperatures they necessarily had a transitory octahedral structure—from the point where the gamma-alpha range began to the point where it ended; but the latter point was passed at a fairly high temperature where diffusion was still active, and therefore the octahedral structure disappeared.

In octahedrites, which contain more than 6 percent nickel, the gamma-alpha transformation was not completed at 450° or 500° where diffusion practically ceases, and therefore the octahedral structure persists.

When an iron with more than 6 percent nickel in cooling reaches the beginning of the gamma-alpha transformation, the gamma phase (taenite) separates in lamellae on octahedral planes, the alpha phase (kamacite) being rejected in plates between them.

The taenite lamellae are not infrequently referred to as having been precipitated, but in reality it is the alpha phase (kamacite) which is precipitated from the original high-temperature gamma solid solution in the form of plates on octahedral planes. Both taenite and kamacite are cubic, but the kamacite plates form along the octahedral planes of the taenite because of the lattice relationship between the two. The interaction of two participating lattices was established by Young, whose conclusions are summarized by Mehl and Barrett (1931). If any phase other than kamacite had precipitated, it would have been on planes other than octahedral.

The separation of the octahedral bands having begun, as transformation proceeds, the alpha plates grow at the expense of the diminishing gamma phase, which becomes progressively richer in nickel. This gamma phase is taenite, which is of variable nickel content depending on the temperature at which it was produced. It may have been produced at a higher temperature and preserved by quick cooling, and thus be low in nickel; or at a lower temperature with slower cooling, when the nickel content would be greater.

After the kamacite has separated it has reached its final alpha state and can have no further structural change. Its nickel content, however, gradually increases, as the temperature falls, up to 6 percent, which is the limit of saturation of iron with respect to nickel; but this involves no change of structure because below 6 percent the nickel-iron solid solution remains unsaturated and homogeneous.

The gamma phase, however, continues to transform into alpha, to an extent determined by thermal conditions. If by reason of low nickel content the transformation takes place in a high thermal range where diffusion is rapid, the transformation is relatively complete; the result is the production of clear taenite segregations, with little or no "spotted" taenite or black plessite.

If a high nickel content retards the transformation to a thermal range where atomic mobility is slight, the transformation will be sluggish and incomplete. As a result there is much black plessite and "spotted" taenite, consisting of a very fine and imperfectly untransformed aggregate of gamma and alpha particles. There is also, with strong etching, more or less grayish darkening even of clear taenite, due to traces of supersaturation, which produces a slight admixture of a gamma-alpha aggregate.

The time required for transformation increases very rapidly below 500° as the nickel content rises, and experiments show that even at that temperature in alloys with more than 8 percent or 10 percent of nickel atomic mobility practically ceases. Therefore when nickel exceeds that proportion, the gamma-alpha transformation cannot be completed artificially before the atoms "freeze in." Below 8 or 10 percent nickel the gamma-alpha zone is traversed at temperatures above 500° where there still is sufficient diffusion to make equilibrium possible.

There is no temperature, however, below which diffusion wholly ceases, although the time required for a structural change may be immeasurably great. As meteorites may have cooled through a period of extreme and unknown duration, it is impossible to place a temperature limit below which some change might not have taken place.

Fineness of octahedral structure.—The mechanism as described is consistent with the fact that the fineness of the Widmanstätten pattern increases with the nickel content. With a low nickel content transformation takes place at a relatively high temperature where diffusion is active. The kamacite therefore precipitates freely in plates, which may reach a thickness of several centimeters, following the octahedral crystallographic planes of the gamma phase, while the relatively small amount of gamma (taenite) migrates easily to the planes of the plates where it segregates. With a high nickel content transformation takes place in a lower range where diffusion is more sluggish. In such case not only is taenite more abundant but the diminished atomic mobility does not permit it to migrate so freely; thus it segregates in lamellae more closely spaced.

Thus the formation of thick plates (showing on a section as wide bands), which took place easily with a lower nickel content and higher temperature, becomes impossible with a higher content and lower temperature. The progressive narrowing of the bands substantially parallels the rise in nickel content; but not exactly, as the successive types of octahedrites overlap somewhat as respects composition and width of bands (fig. 8). With the same composition greater rapidity in cooling would tend to produce a finer Widmanstätten structure.

Vogel's theory.—The foregoing outline of the process reflects the current prevailing views of metallographers and is consistent with the early iron-nickel equilibrium diagram of Osmond and Cartaud (fig. 4), upon which the now generally accepted diagrams are based, which postulated the existence of two phases although at that time two phases had not been produced in artificial alloys. That was accomplished first by Benedicks (1910), who succeeded in producing characteristic Widmanstätten structures, in some cases visible to the eye. A macroscopic structure of great perfection was recently produced by Mehl and Derge (1937). Vogel, however (1925, 1927), did not accept the production of an artificial Widmanstätten structure as confirmation of Cartaud's hypothesis, arguing that the existence of a eutectoid horizontal line extending from 6 to 30 percent nickel, which he deemed essential to that theory, had not been established. He ascribed the origin of the structure (both natural and artificial) not to the gamma-alpha transformation but to an earlier delta-gamma transformation. Figure 9 shows the range in which this transformation takes place, which is brief and at a very high temperature.

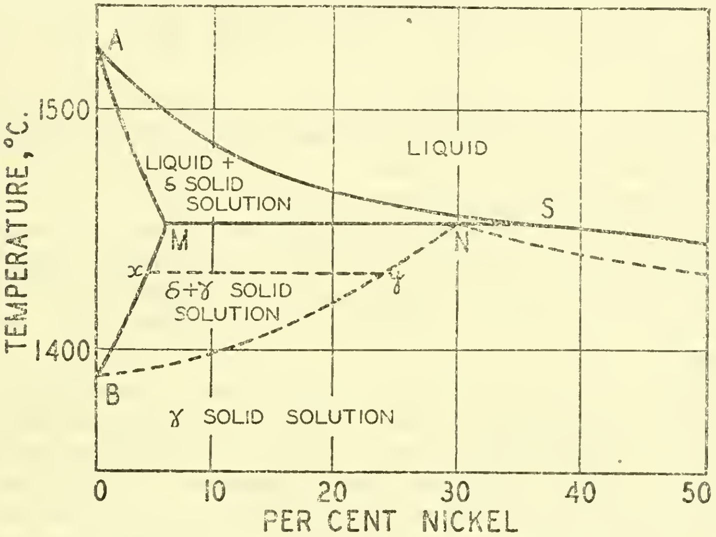

Figure 9.—The delta-gamma transformation in nickel-iron.

The Vogel mechanism.—In artificial irons containing carbon the delta range between the melt and gamma phase is small and its effects are negligible; but in iron-nickel alloys its width is greater and it extends to about 30 percent nickel. If the percentage of nickel is more than that, the alloy passes directly from the melt to the gamma phase.

According to Vogel, in the range from 0 to 35 percent nickel solidification begins on the line AS. When an alloy of the composition of octahedrites (6 to 14 percent nickel) cools to the line MS a heterogeneous structure begins to develop; the primary delta solid solution separates into two components in equilibrium—a nickel-poor delta solid solution of the composition M (kamacite) and a nickel-rich (taenite) of the composition S, with about 35 percent nickel. Later the two components in equilibrium have the compositions x and y, and after passing the line BN the alloy is wholly gamma.

Thus, according to his view, the delta iron, possessing the same crystalline structure as alpha kamacite, crystallizes directly from the melt in dendrites, growing into skeletal forms, which in the delta-gamma range become lamellae having octahedral planes with the taenite segregating between them, producing the Widmanstätten structure.

On further cooling the delta completely transforms into the gamma phase with a remnant dendritic pattern and the alloy again becomes homogeneous if cooling is slow. But if sufficiently rapid, Vogel held, the structure may be preserved.

Objections to Vogel's theory.—Meteoric irons, however, cannot be assumed to have generally undergone quick cooling. Many features of their structure, its coarseness, and especially the unigrain character of large masses, indicate extremely slow, even secular, cooling.

On other grounds also Vogel's theory does not seem acceptable. It is based upon the fact that all the earlier iron-nickel diagrams (before the delta-gamma transformation was established) indicated that an artificial iron-nickel alloy, regardless of its proportions, passes from one phase to another without any miscibility gap—in other words, the alloy always consists of one structural component. Thus the presence of two distinct components in the octahedral structure, representing two coexisting phases, was not explainable. The delta-gamma range, in which two phases were found to coexist, seemed to Vogel to furnish the answer.

It has been established, however, that two phases do coexist in the gamma-alpha range in artificial iron-nickel alloys. In meteoric irons the high and low nickel components are seen to produce a regular paraeutectoid structure in nickel-rich ataxites. Such structures clearly cannot arise in the delta-gamma range, nor can they be explained by the influence of phosphorus (in accordance with an opinion expressed by Vogel in 1927) because such structures are highly developed in irons that are practically P-free (Deep Springs 0.06 percent, Iquique 0.05–0.07 percent P).

Vogel's view was rejected by Kasé (1925) soon after it was announced, who concluded that the origin of the structure is substantially as outlined earlier in this chapter, and by other investigations.

The results of X-ray analysis also support the view that the structure is formed at a relatively high temperature during very slow cooling (Mehl and Derge, 1937; Derge, 1939).

Another reason why the Vogel theory is untenable is the fact that it requires a face-centered cubic phase to form upon the octahedral planes of a body-centered cubic phase. In such a case the face-centered phase would form in plates along the dodecahedral planes of the body-centered phase.

The Vogel theory also is inconsistent with the fact that although troilite inclusions solidified at 970°, nevertheless they obviously are older than the surrounding octahedral structure, which abuts against them uncomformably.

These and other considerations, including the known octahedral crystalline habit of the gamma phase, seem to confirm the earlier and generally accepted view as to the origin of the Widmanstätten structure.

A low-temperature equilibrium.—The investigations of Owen and Williams (1938) and of Bradley (1939) with X-rays and heat treatment indicate the existence of two phases in equilibrium between 350° and 580°. Such a two-phase equilibrium, previously not believed to exist in artificial nickel-iron, was produced by annealing the alloy at 580° followed by very extended cooling, in which a gamma phase developed with about 30 percent nickel. The structure produced between 350° and 380° was very minutely crystalline.

This led these investigators to the conclusion that the coarse octahedral structure in meteoric irons could have been produced either by secular cooling within the 350°–580° range or by repeated heatings and successive coolings within that range, which would have the same effect as a single protracted cooling. This latter condition of production, they point out, might be met if a meteor traveled in an elliptical orbit that brought it periodically near the sun.

Some of the finer structures found in nickel-rich ataxites might conceivably have been produced in such a manner, but the author cannot accept the conclusion that the coarser Widmanstätten structures arose in so low a temperature range. It does not seem consistent with the existence of a very coarse octahedral structure in irons with only 6 or 7 percent of nickel, which naturally would have arisen in a relatively high temperature range in which diffusion was active. It is also a pertinent fact that the coarse precipitation of phosphide on the crystallographic planes in Horse Creek (pls. 60, 61) show an $Fe–Fe_3P$ eutectic structure that could not have formed at a temperature much below 1,000°, and likewise the formation in the solid state of rhabdites of perfect crystalline form in kamacite plates could only have taken place at a much higher temperature range than 350°–580°. All the observed structures in octahedrites are consistent with the theory of their production by slow cooling from the gamma range.

Cosmic heatings.—There is the further objection that the operation of such a mechanism could be only occasional, whereas meteorites of any given range of composition show a marked uniformity of structure. The hypothesis of such successive reheatings is of itself admissible. Certain meteors have been observed to pass at perihelion within the orbit of Mercury. A meteor would have to pass considerably within that orbit to be heated as high as 350°, though it may fairly be assumed that some may do so. But such cases would be exceedingly rare in comparison with the overwhelming proportion that move in orbits much farther from the sun.

The structures of meteoric irons indicate uniformity in the conditions of their production. Microscopic examination of a large number of irons reveals a strikingly regular progression in structure from the coarsest octahedrites to the highest nickel ataxites, each type of structure corresponding with a certain range of composition. Thus it seems needless to invoke the theory of a mechanism that necessarily would be exceptional to explain structures that are almost always present in substantially the same form within any given range of nickel content.

Transformation structure.—An important structural feature in meteoric irons, which apparently was first correctly interpreted by Vogel, is an acicular structure produced in the gamma-alpha range, which may conveniently be termed the transformation structure.

A feature termed by him transformation figures (Umwandlungsfiguren) was described by Vogel (1927) as a product of the delta-gamma transformation. It appears in artificial iron-nickel alloys as a network of very minute oriented needles somewhat suggesting the Widmanstätten structure. He stated that it also occurs in meteoric irons, mentioning as one example Smith's Mountain (pls. 38, 50). Owing to the unstable and transitory character of the delta-gamma structure, however, that explanation was unsatisfactory; for the question naturally arises how such a structure could have been preserved through the gamma range in irons of low or moderate nickel content.

In a later discussion (1932), however, the same author does not deal with the supposed delta-gamma figures but describes at length the transformation figures arising at lower temperatures in the solid state. These he explains as the result of the gamma-alpha transformation—minute alpha needles (lamellae) developing in the gamma iron, similar to the martensitic structure in very low-carbon steels.

The explanation is quite satisfying for this important structure, which is seen in many octahedrites. It is common and often very strongly pronounced (e.g., Trenton, Seneca Township, Canton, Smith's Mountain, Thunda; pls. 35–38, 77).

It often has a strongly oriented acicular pattern, producing the effect termed "hatching"in the bands of octahedrites, as well as the strong sheen that such bands exhibit, which formerly was attributed to Neumann lines or other causes.

Though characteristic of octahedrites, this structure occasionally is found in irons of such low nickel content that presumably they should be wholly in the alpha phase. For example, in Primitiva, a nickel-poor ataxite (Ni–Co 5.61 percent), the structure is strongly developed (pl. 10), and it is also found in New Baltimore (pls. 76, 77), which has a Ni-Co content of 6.74 percent and is wholly hexahedral in its microstructure. An analogous structure is found in spots in San Francisco del Mezquital (Ni–Co 6.33), a nickel-poor ataxite (pl. 78).

In such cases the structure of gamma-alpha needles may have been a result of rapid cooling, lowering the transformation to a range of temperature in which the kamacite and taenite could not agglomerate because of slow diffusion, a process analagous to the formation of martensite in artificial irons.

"Spotted" taenite and kamacite.—Another product of imperfect transformation is the so-called "spotted" (more aptly "darkened") taenite, which has previously been referred to, and the similar appearance less often observed in kamacite. Taenite bodies with darkened cores are so common that they might be called the rule rather than the exception; many examples appear in the plates. They are found almost always in medium and fine octahedrites in which the nickel content was high enough to retard transformation to a low range where it could not be fully completed because of the rigidity of the mass. Atomic mobility being insufficient to permit complete coalescence of the taenite, an aggregate of very fine alpha and gamma particles was left, appearing black because of the strong attack of the etchant around the particles.

Even apparently clear taenite often shows, with strong etching, more or less grayish darkening, indicating that transformation was not quite perfect. The taenite, being slightly supersaturated with respect to kamacite, has traces of a gamma-alpha aggregate. In coarse octahedrites transformation took place in a thermal range so high as to permit a full segregation of the two phases, and taenite is usually clear.

Kamacite may be similarly darkened by the presence of a gamma-alpha aggregate when transformation was incomplete. The author has rarely observed it, but a good example is seen in Trenton (pl. 78) where kamacite lamellae in a coarse plessite field are thus darkened. The plessite field being richer in nickel than the surrounding mass, transformation within it would naturally be retarded.

The "ragged" structure.—A structure somewhat acicular in appearance, occurring in taenite bands and (it is said) less often in kamacite, is referred to by some of the more recent German writers as the "ragged" structure (Fetzenstruktur) and has been ascribed to twinning in the gamma phase.

Kamacite, like ferrite in artificial irons, develops a granular structure in cooling through the gamma range, and also on reheating into the gamma range. The two types of grains differ in that those produced within the alpha range are free from twinning; while those produced in the gamma range are characterized by abundant twinning, which disappears normally when the iron in cooling changes to the alpha phase. Such twinning might be preserved in a high-nickel taenite which remains in the gamma phase to room temperature (e.g., Octibbeha, pl. 34).

This explanation is given by Vogel for the formation of the ragged structure, of which he gives as a characteristic example a photomicrograph of a taenite lamella in the Burlington meteorite (Vogel, 1927, fig. 11). He states that it is not due to a separation of nickel-rich and nickel-poor components but is merely an evidence of gamma twinning preserved by rapid cooling—especially when transformation is retarded by a high-nickel content, which accounts for its being more often observed in taenite than in kamacite.

The author, however, has been unable to find in Burlington a structure of the nature indicated by the published photomicrograph referred to. Recent photographs of many such lamellae in Burlington, at higher magnification and possibly more perfect than those taken by Vogel 15 years ago, indicate a transformation structure having only a faint resemblance to real gamma twinning, as shown in Octibbeha (pl. 34) and in artificial irons. Hundreds of photographs of octahedral irons, at various magnifications, also have failed to reveal an example of twinning in kamacite. The author therefore is inclined to the view that the ragged structure is a form of the gamma-alpha transformation structure already described, which is of frequent occurrence and in a great variety of forms.

Granulation already has been discussed in Chapter IX, and secondary granulation as the result of reheating is further considered in Chapter XIII.

Granular octahedrites.—Certain forms of octahedrites have been designated as brecciated, or breccialike (Ob), and Brezina's classification divided these into several subgroups named after typical examples. Altogether about half a dozen irons have been thus classified.

In a number of cases the author doubts whether this classification is applicable. For example Zacatecas (Ni–Co 6.55 percent; Cohen, 1897) in the particular specimen studied shows no octahedral character, either macroscopic or microscopic, but resembles a typical granular hexahedrite. The same is true of Barranca Blanca, the specimen studied being apparently a granular hexahedrite somewhat resembling Kendall County. The Ni–Co content of 8.66 percent found by Fletcher (1889, p. 263) would seem to be high for such a structure.

Four Corners, however, would clearly fall within the classification, although the term granular would be more appropriate than brecciated. That unique iron shows a pattern of very large grains in each of which a highly perfect fine octahedral structure has developed on planes that are unrelated in the different grains. The analysis by Whitfield (in Merrill, 1924) showed 10.16 percent Ni–Co, which is consistent with the octahedral pattern.

Santa Rosa, Colombia, also would come within the classification. This iron (known also as Rasgata and Tocavita) shows unrelated areas of fine octahedral pattern. Its Ni–Co content as found by Manteuffel (Meteoreisen-Studien, pt. 3, p. 113, 1894) was 7.10 percent.

An anomalous iron.—A meteoric iron of anomalous type is Horse Creek (pls. 60, 61). In this extraordinary iron, which to the eye resembles an octahedrite, there are no lamellae of taenite but in their place lamellae of schreibersite have formed in a Widmanstätten structure, the mass consisting wholly of kamacite and phosphide. The brittleness of the latter causes the mass to break very easily with a highly perfect cleavage which might easily be mistaken for octahedral.

The structure in general resembles that of a fine octahedrite, although the phosphide lamellae are much finer, much more numerous and closely spaced, and of extreme regularity. Some are fairly thick, sufficiently so to reveal a eutectoid structure with picrate etching; but for the most part they are very tenuous, appearing even under high magnification as extremely fine and straight black lines. Occasionally such fine lines thicken and coalesce with the broader phosphide lamellae, thus dispelling any doubt that they are phosphide.

Minute phosphide needles and extremely fine particles are thickly disseminated in the angular interstices of the octahedral pattern, being most abundant in the centers of such fields and sparse or absent near the bounding phosphide lamellae.

Though Horse Creek resembles an octahedrite, its planes are not octahedral, as the phosphide is tetragonal and because of the relation of its space lattice with that of iron it would precipitate on other than octahedral planes. This was true of a Widmanstätten structure produced by Mehl, Barrett, and Jarabek (1934) from a solution of 3.2 percent phosphorus in alpha iron, though the exact crystal structure of the precipitate was not determined. That the planes in Horse Creek are not octahedral is apparent from plate 60, where deviations from the octahedral planes are apparent.

Transitional octahedrites.—When the octahedral structure is normally developed it is easy to assign an iron to its proper class by simple measurement of the bands. The transitional low-nickel and high-nickel types, however, give rise to differences of opinion.

The distinction between coarsest octahedrites and granular hexahedrites in some cases is doubtful, there being large areas with diversely oriented sheen in which some see traces of an octahedral pattern and others do not. Ainsworth, for example, with 6.9 percent Ni-Co, has always been classified as a coarsest octahedrite; yet the author's specimen, a full-sized slice, has both the general appearance and structure of a granular hexahedrite, with no suggestion of an octahedral pattern.

El Burro, a newly reported Mexican iron with 6.36 percent Ni-Co, has a fairly recognizable octahedral pattern with bands one or two centimeters wide. In Santa Luzia de Goyaz (Ni-Co 6.23 percent) only local traces of an octahedral pattern are discernible, most of the mass being made up of very large and irregular grains with rosette inclusions of schreibersite similar to Ainsworth. In both of these irons the Ni-Co content is no greater than that of some hexahedrites.

Mount Joy (Ni-Co 6.40 percent), which Linck and Brezina called a hexahedrite and Berwerth an octahedrite, the author considers a typical granular hexahedrite, its Ni-Co content being little above that of a number of irons in that group. The same is true of Central Missouri, the only available analysis of which gives the very low, perhaps too low, percentage of 4.80 Ni-Co; its large grains, reaching dimensions of inches, seem altogether irregular. This iron is recorded in museum catalogues as a coarsest octahedrite, though Weinschenck apparently regarded it as a hexahedrite.

New Baltimore (Ni-Co 6.74 percent) presents an anomalous feature. It is made up of large grains, like Central Missouri and others, which have a characteristic microstructure, with no visible taenite. One large grain, however, is filled with a very distinct medium to fine octahedral pattern. No analysis or microscopic examination was made of this grain, but obviously its nickel content is higher than that of the general mass.

In the author's opinion the criterion of an octahedrite should be the presence of a clear and dominant octahedral pattern. Composition alone is not an exact criterion; for the proportions of Ni-Co in the two groups overlap, taenite and plessite may be lacking in a clearly marked octahedrite (e.g., Osseo, Ni-Co 6.62 percent), and again both may be present in a typical hexahedrite (e.g., Otumpa, Ni-Co 5.68 percent). It must remain a matter of opinion in any given case whether an iron showing signs of an indistinct, subsidiary or localized octahedral structure should be termed a hexahedrite or a transitional coarsest octahedrite.

A similar uncertainty attaches to the classification of high-nickel transitional types. Here again the criterion should be the presence of what the observer regards as a definite octahedral pattern of kamacite bands. It is not enough that spindles or needles of kamacite should show octahedral orientation; that appearance is often found in very high-nickel ataxites—even including San Cristobal (Ni-Co 26.60 percent) and Limestone Creek (Ni-Co 30.47 percent). Indeed if kamacite particles in a high-nickel iron (above 10 percent) show any traces of crystalline orientation it would necessarily be octahedral; for in such irons the atoms become "frozen in" and diffusion practically ceased around 500°, and thus any orientation remaining at room temperature would be in conformity with the octahedral planes of the gamma phase.

Thus Cowra (Ni-Co 14.25 percent), which is classed as a finest octahedrite, seems to the author clearly to be an ataxite, differing in no essential respect from Wiley and Monahans. Laurens County (Ni-Co 14.21 percent), on the other hand, though exhibiting some of the same structural features as the above three, is clearly an octahedrite because it has a striking Widmanstätten pattern. It is possible that the new analyses of these irons would show a higher nickel-cobalt content in the former than in the latter.

XII. PLESSITE; NICKEL-RICH ATAXITES

Genesis of plessite.—Plessite may be regarded as a supersaturated solid solution of taenite with respect to kamacite, its form depending upon the conditions of temperature and rate of cooling. Though occurring characteristically in octahedrites, it is not necessarily a part of the Widmanstätten structure; for, as mentioned in Chapters III and X, it is sometimes found in hexahedrites.

In octahedrites the most convincing explanation is that plessite is an alpha-gamma mixture formed during transformation—a coarse structure if formed in a high thermal range, an extremely fine structure if formed at a low temperature. Plessite fields are remnants of the gamma phase left in the interstices of the octahedral network, and their structure was developed in the solid state.

Coarse plessite prevails in the coarser octahedrites, being exceptionally found in the fine ones and never in the finest. The coarse and perfect separation of kamacite and taenite, the former usually predominating, reflects a low or moderate nickel content, and therefore transformation in a relatively high thermal range where atomic mobility makes possible a rapid and complete separation.

The absence of a marked taenite border along the interface of coarse plessite fields (e.g., Seeläsgen, Kenton County, Bear Creek, Smith's Mountain, Roebourne) also is an indication of formation at a relatively high temperature, the segregation having been so complete as to leave little residual gamma phase in the surrounding mass to form a border later. In the fine and finest octahedrites, which being nickel-rich transformed at much lower temperatures, the fine to dense plessite fields have distinct, often wide, taenite borders.

Vogel's views.—Vogel, who held that the Widmanstätten structure originated immediately after the primary solidification, assigned the formation of light plessite to the same cause. His original explanation of dense plessite (1927) was that it is identical with dense ataxites and that its structure is due largely to the presence of phosphorus—that is, that it is a eutectoid representing the equilibrium of a ternary iron-nickel-phosphide alloy with more than 0.2 percent of phosphorus. (According to his view there could not be such an equilibrium of two phases in a binary iron-nickel alloy.) This explanation seems untenable, for dense plessite is found in irons that are nearly or wholly phosphorus-free—e. g., San Francisco Mountains, which has none.

In a subsequent treatment of the subject (1932) he ascribed the origin of dense plessite to transformation in the solid state, a secondary crystallization due to the gamma-alpha transformation. According to that view the very fine structure, which shows black with ordinary etching but is not affected by sodium picrate, represents an alpha-gamma mixture—not a two-phase equilibrium structure, but an intimate mixture of gamma and alpha solid solutions, sometimes with transformation figures (gamma needles in alpha kamacite); and that it indicates spots not of phosphorus but of nickel enrichment.

This view the author also regards as untenable, for the existence of two phases in artificial irons has been proved, and the structures in both plessite and ataxites are consistent with that fact.

A two-phase structure.—The conclusion seems inescapable that fine and dense plessite, and nickel-rich ataxites, all represent variations in a two-phase equilibrium structure.

With the nickel content of coarse octahedrites the transformation would be completed at a relatively high temperature, at which the atomic mobility of the mass would permit a comparatively rapid and perfect phase separation—that is, light or "normal" plessite with a coarse structure, the taenite clear because transformation is complete and an equilibrium structure has been attained.

In a high-nickel iron, however, the process would be much depressed, and the gamma-alpha transformation thus retarded to a temperature at which there would be greatly reduced atomic mobility. In a mass of such rigidity the transformation would remain incomplete, and instead of a complete separation of the two phases (as in the fine kamacite bands and the lamellae and skeletal growths of taenite in light plessite fields) the product would be a fine aggregate of kamacite and taenite.

This aggregate first takes the form of a thick dispersion of taenite dots in kamacite, forming the darker but easily resolvable plessite, often banded. With a higher nickel content there is a more refined structure, the dots being so minute and thickly crowded that we have dense plessite, resolvable only with high magnification. With nickel above 15 percent (sometimes less) a more or less perfect paraeutectoid structure is produced, that of the nickel-rich ataxites, when there has been a sufficiently long sojourn at lower temperatures.

Transformation is retarded by rapid cooling to a low temperature when diffusion is slight and a dense black structure resembling sorbite or troostite in artificial irons is produced. It ordinarily is unresolved, but it is more or less resolved at high magnification (pls. 12, 14, 16, 43). It may show a coarse acicular oriented pattern, but the black needles themselves are composed of an extremely fine gamma-alpha aggregate. Such retarded or arrested transformation also accounts for the darkened spots and cores so often observed in taenite bodies ('spotted" taenite). When the transformation is nearly, but not absolutely complete, a slight graying of taenite may appear.

Although dark plessite does not depend upon the presence of phosphorus, all plessite fields are remnants of the gamma solid solution after the separation of the kamacite bands and taenite lamellae, and if the mass contained phosphorus it must have been more largely concentrated in these interstitial remnants. That would tend to promote the formation of paraeutectoid structures by depressing the gamma-alpha transformation. The same structures, however, form in nearly and quite phosphorus-free irons.

Segregated kamacite does not wholly disappear even in very high-nickel irons. Kamacite spindles or particles are found in San Cristobal (Ni-Co 26.60 percent) and even in Limestone Creek (Ni 29.99 percent, Ni-Co 31.47 percent). They have, however, wholly disappeared in Santa Catharina (Ni 34.37 percent, Ni-Co 35.87 percent). In Octibbeha (Ni 62.73 percent) the mass is clear and structureless, with no trace of gray darkening even with the strongest etching.

The nature of kamacite needles.—In Cape of Good Hope (Ni-Co 16.62 percent) there is an obscure paraeutectoid groundmass consisting of fine wavy and branching bodies of light and dark structural components (pl. 22). Occasional white spindles or needles, with white borders, appear in the groundmass. Pfann referred to them as kamacite bordered by taenite. Brezina considered the cores to be kamacite or schreibersite. Berwerth was of the opinion that they consist of schreibersite with kamacite borders and that the light wavy lines in the surrounding groundmass are kamacite, while the darker component is eutectoid plessite. In the analogous structure of Cowra (Ni-Co 14.25 percent; pl. 17) the spindles were referred to by Brezina as kamacite, but Cohen (1905) considered them to be taenite.

The solution of this puzzling question presents an interesting illustration of the value of modern metallographic methods. Cohen and Brezina did not have the use of vertical illumination, and even Pfann and Berwerth could not avail themselves of sodium-picrate etching. When that treatment is applied to such irons, no darkening occurs either in the spindles or in the light component of the groundmass, proving the absence of schreibersite. Moreover, at high magnification and with ordinary etching, the borders of the spindles can be seen to merge with the lighter component, and therefore must be identical with it. Perfect examples of such merger may be seen in certain other irons in which the structure is clearer than in Cape (Deep Springs, Tucson, Limestone Creek, Laurens County; pls. 16, 20–22, 31).

A further question arises, however, from the fact that this light component in the groundmass is not everywhere perfectly clear but darkens slightly with strong etching even where the coalescence begins. But the analogies of many other irons prove that taenite is thus darkened, more or less, because of varying degrees of supersaturation whereby the transformation of the gamma phase was not quite perfect. Thus it becomes plain that the lighter component is actually identical with the clear taenite borders of the needles, many small areas appearing darkened.

The establishment of the nature of the needles was peculiarly difficult in the case of the Cape iron because the taenite borders are separated from the groundmass by a dark confused zone, and no such coalescence can be observed. Indeed the problem would not be simple even with metallographic methods, if its solution depended upon the study of that iron alone.

Recapitulation.—The following conclusions therefore can be satisfactorily drawn in the case of nickel-rich ataxites:

They are not a secondary product of alteration from a primary Widmanstätten structure but represent an original two-phase equilibrium structure produced by transformation at a low temperature, perhaps completed at as low a point as 350° or 360°. The transformation was retarded to such a low range by the high proportion of nickel, the retardation being perhaps sometimes increased by the presence of phosphorus.

The structure is more or less characteristically eutectoid in appearance, though the areas of gamma and of alpha phases are not of definite composition. One component appears as islands within the other when the structure is typically developed (Morradal, pl. 28; Linville, pl. 24; Ternera, pl. 25).

Needles or spindles of kamacite, when present, represent an incipient octahedral structure, which developed imperfectly because of the low temperature of transformation. They may be oriented but are less often so in very high-nickel irons. By attracting to themselves the alpha phase (kamacite) of the immediately surrounding mass, a border of pure taenite is left around them, which coalesces with the same component in the groundmass. The paraeutectoid is essentially plessitic, and its structure sometimes appears identical with that of some plessites found in octahedral irons.

With very light etching the two components may both appear perfectly clear and indistinguishable; or even the kamacite may darken slightly because of cold-working, as explained in Chapter III. With stronger etching the kamacite is clear, but the taenite usually becomes more or less gray, or develops darker areas, because of supersaturation with respect to kamacite.

Nickel-poor ataxites do not present a primary structure, but are a product of alteration by reheating. This is discussed in the following chapter.

Spheroidized taenite in plessite.—Mention has been made of a peculiar type of plessite in which minute spheroids of taenite are dispersed in a matrix of clear kamacite, observed in Otumpa, Seeläsgen, and Leeds (pl. 46).

This peculiar structure suggests the spheroidizing of cementite (iron carbide) in steel (pl. C) as the result of annealing in a certain thermal range, and it may have been produced in an analogous manner. Taenite not infrequently shows some tendency to spheroidization, though on a smaller scale and less perfectly, in the minute droplets found in light plessite fields. The development of such very minute spheroids is exceptionally perfect in certain fields in an unidentified iron illustrated in plate 74. The larger spheroids, first referred to, many of which show incompletely transformed cores, are evidently the product of slower growth.

Both spheroidized taenite and the lamellar form resembling the structure of pearlite are obviously due to a rate of cooling too rapid to permit coalescence. Thus in the unidentified iron shown in plate 74, which bears evidence of strong reheating, owing to the rapidity of cooling the taenite was entrapped in the interior of the large kamacite grains, where it coalesced into minute spheroids instead of migrating to the grain boundaries. In the same iron, in a lamella of dense plessite or darkened ("spotted") taenite, in which the gamma phase was much more abundant, it segregated in cooling partly in spheroids and particles, and partly in a pearlitic pattern of lamellae, instead of migrating to the edges to form the usual border. In the other three irons mentioned, the plessite fields show a limited development of the pearlitic pattern, in addition to the larger areas of spheroids.

XIII. HEAT ALTERATIONS

Sorby (1887) early pointed out that structural changes were produced in octahedral irons by reheating, and he suggested a classification of meteoric irons according to whether they had been reheated but did not indicate the nature of such heating. Cohen (1905) mentioned the observations of Sorby and of Brezina and discussed briefly the newly expressed theory of Berwerth (1904) that ataxites in general are derivatives of octahedral irons through reheating. This theory Cohen did not accept, aptly pointing out that many ataxites have compositions unknown among octahedral irons.

A decade later central illumination had come into use in the study of meteoric irons, and some of its important revelations were embodied in publications by Pfann (1917) and Berwerth (1918) as the result of investigations begun by them jointly in 1914. Pfann, disregarding the factor of reheating, built up convincingly a continuous series of structures in accordance with the iron-nickel diagram as then accepted. Berwerth's memoir is confined to the interpretation of illustrations of 14 ataxites. Eight of these he treated as natural products, in substantial accordance with Pfann's views; the other six he classified as products of artificial heating.

Earlier researches by Berwerth (1905) were noteworthy as establishing the fact that the appearance of the kamacite in octahedral bands is markedly altered by heating, though he found the bounding taenite unchanged. He apparently did not study the effects upon plessite. Rinne and Boeke (1907) carried similar investigations further, finding that the taenite in fine plessite fields became diffused by heating, and that the fields took on the appearance of the altered kamacite in the bands. From this fact the important conclusion was drawn that the structure of such plessite is not one of primary crystallization from the melt but a transformation product formed during the cooling of the solid solution. In more recent years this field of study has been thoroughly explored, notably by Kasé (1925) and by Vogel (1927, 1932), who made exhaustive researches involving the heat treatment of meteoric irons and related artificial alloys.

Artificial heating.—As to nickel-poor ataxites being a product of artificial heating, there are a few cases where that explanation might possibly be entertained. Of the six regarded by Berwerth as artificial metabolites, three have no definite history of such heating. In the other three cases that conclusion might be sustained in the case of Hammond because it was heated in a forge and a piece cut off. One of the Babb's Mill irons (the Troost iron) also was heated to determine whether it contained silver.

Such heatings may have been high enough and long enough to produce structural changes, although that seems improbable. In the case of Rafrüti, which for some years had been heated by a farmer in winter for domestic purposes, it does not seem possible that any change could have been produced. Though according to Tammann granulation begins to appear after prolonged laboratory heating at as low a point as 400°, any ordinary heating sufficient to produce even incipient granulation in kamacite could hardly be less than 550° continued for many hours (Kasé, 1925), which would correspond with a blood-red heat. Before schreibersite would begin to melt the temperature would have to be about 1,000°, which would produce a very bright (orange or lemon) red.

The failure of a rather strong artificial heating to produce structural changes is illustrated in the case of the Cedartown hexahedrite. The house in which it was kept was completely destroyed by fire and the meteorite later recovered from the ashes. Though it presumably may have been heated for a time to a dull red heat, the microstructure shows no trace of alteration. No new granulation appears, schreibersite needles show no diffusion, and even Neumann lines remain perfect.

We may fairly conclude that artificial metabolites, though perhaps sometimes produced, are rare.

Natural reheating.—As to alterations of structure by natural reheating, there is no uncertainty. The evidences of it are conclusive, and the same effects have been produced experimentally under controlled conditions.

Natural reheating is of two types—terrestrial and cosmic. The former is brief, due to heat generated during the flight of the meteor through the atmosphere, the structural changes being superficial and usually only incipient. Cosmic reheating, reflected in alterations of the general structure throughout the mass, must have been higher and of longer duration, with probably slow cooling.

Terrestrial heating, producing the familiar "zone of alteration," will be discussed first because the results were recognized and interpreted before improved methods of research revealed the effects of cosmic heating.

Zones of alteration.—Iron meteorites often show on etched slices a peripheral band of varying width, up to a centimeter or more, in which ordinary etching develops a dull granular surface. In octahedrites the contrast with the inner Widmanstätten structure is conspicuous to the eye. This is called a zone of alteration, the result of superficial heating during flight through the atmosphere (pl. 71).

Though described in numerous octahedrites, zones of alteration were observed by the older writers in but few hexahedrites or ataxites. Cohen mentions only half a dozen of the former and three of the latter. Such zones, however, in the absence of metallographic methods, would be likely to escape observation except in octahedrites. The author has found them in many hexahedrites and ataxites, and there is no reason to assume that they are not equally common in all types of meteoric irons.

Within the zone are found the usual indices of reheating—disappearance of Neumann lines, granulation of kamacite, partial diffusion of schreibersite, and more or less alteration of dense plessite due to the partial diffusion of taenite particles. These changes in various types of iron are shown in plates 71–74.

In hexahedrites the zone of alteration usually shows fine granulation, strongly marked, and diffusion of phosphide inclusions. The resulting structure is in cases identical with that of nickel-poor ataxites (cf. plates 9 and 58). Rhabdites lose their angular outlines and become shapeless droplike particles, or may disappear entirely, leaving only spots of phosphide enrichment which darken with picrate etching. Masses and the larger needles of phosphide commonly show a thorny or prickly outline, caused by the diffused phosphide invading the surrounding mass along grain boundaries (pls. 58, 59). Such inclusions often show a phosphide eutectic structure, as described in the following chapter.

In nickel-poor ataxites the author has not observed a distinct zone of alteration. This might be expected because, as explained later in this chapter, such irons are a product of alteration by cosmic heating, which already had extended throughout the mass. In those nickel-rich ataxites in which the structure consists of a very fine gamma-alpha aggregate, no noticeable change would be likely to occur. In Freda, which has a marked acicular gamma-alpha structure, that appearance is obliterated in a very narrow zone. In Morradal the paraeutectoid two-phase structure, very perfect and uniform in the interior of the iron, becomes coarser near the surface by the agglomeration of the minute kamacite and taenite areas; the author, however, doubts whether this difference is due to superficial heating.

Extent of heating.—By reason of the short exposure to the heat generated in atmospheric flight, and the extremely cold interior of the mass, the depth of alteration in such zones is slight. The alteration is sufficient to obliterate Neumann lines, which disappear with even very short heating in the range from 800° to 1,000°, and to produce a definite granulation of kamacite. Both changes can usually be observed in an incipient stage near the inner boundary of the zone. The heating usually is insufficient anywhere to alter even thin taenite lamellae, or to cause more than incipient diffusion in plessite fields.

These observed effects are consistent with the results of experiments by various investigators that have indicated that a sojourn of a few seconds at around 1,000° would produce such changes, but that a more prolonged or higher degree of heating would cause more extensive alteration.

Fusion crusts.—The superficial heating of an iron meteorite during its flight through the air probably always produces a coating of magnetic oxide (ferrosic oxide, $FeO.Fe_2O_3$, or Fe_3O_4), which often remains as a fusion crust on irons that have recently fallen, or that have lain on the surface of the earth in arid regions. Such a crust is black, slightly shining when fresh, and usually very thin, commonly not exceeding in thickness heavy paper or thin cardboard. Occasionally it has a slaggy appearance, and sometimes it exhibits a flow or drift structure of fine striae or ridges.

The substance of the fusion crust, which also penetrates cracks in the mass, was called "Eisenglas" by Reichenbach and that term was somewhat used by the older writers. It is essentially ferrosic oxide, although it may to some extent be a mixture of ferric and ferrosic oxides, and it may also carry in solid solution a little sulphide or phosphide derived from inclusions of those substances. Large nodules of troilite thus melted out may have produced, or started the production of, the rounded cavities so conspicuous on the surface of Canyon Diablo and some other irons.

Intrusive oxide.—The black substance filling cracks extending from the surface toward the interior of many irons was early recognized as identical with that of fusion crusts. In such cases it extends to the uttermost limits of the cracks—as might be expected, inasmuch as it was forced into them by extreme air pressure as fast as the cracks themselves were formed.

In octahedrites the oxide may invade the structure to some extent, especially near the inner terminations of the cracks, penetrating for short distances along kamacite bands. It is also apt to follow or invade inclusions of schreibersite because of its low fusibility.

In appearance under the microscope magnetic oxide and hydroxide are often indistinguishable, but the intrusive oxide usually can be recognized by the manner of its occurrence.

An area of intrusive (magnetic) oxide resembles a bay or river, with rounded and clear-cut boundaries. All the normal structures within it are wanting, while the structure in the adjoining mass is undisturbed. In cracks the oxide sometimes shows structures resulting from quick cooling (pl. 69).

The hydroxide, on the other hand, invades the mass irregularly, occupying individual grains or penetrating along grain boundaries. Taenite particles in plessite may be unaffected, and taenite lamellae often remain unchanged, preserving perfectly the outlines of the octahedral structure (pl. 69). The hydroxide also may surround perfect rhabdites, which would have been melted if the oxide were intrusive.

Dendritic crystallization.—A unique effect from the action of intrusive oxide was observed by the author in Seneca Township (1939) and in Wood's Mountain (1939), in both of which the oxide fills small depressions in the surface and encloses minute rounded areas of iron exhibiting a beautiful dendritic crystallization, a structure which it is believed had not previously been observed in meteoric irons (pl. 70). The author also found such areas in Carlton and Reed City.

As dendrites are produced by rapid cooling from the melted state, they could not exist as a primary structure in the mass of an iron meteorite. It is evident that the iron was invaded slightly at certain points by the superheated liquid solution of iron and ferrosic oxide formed on the surface during flight, which accumulated on the rear side where it remained long enough to penetrate slightly at favorable spots. The curvature of the octahedral structure around a number of such spots suggests the former presence of inclusions of troilite, which would have melted quickly and thus facilitated such invasions.

As the oxide-iron solution quickly cooled the oxide was rejected, the iron separating in rounded droplets, which developed a dendritic structure oriented with reference to the surrounding oxide, somewhat as dendrites in steel are oriented with reference to the enclosing mould.

That the iron droplets solidified first is indicated both by the structure and by the relative fusibility of the two components. Though purified ferrosic oxide melts at from 1,527° to 1,600°, natural magnetic oxide has been found to melt at from 1,210° to 1,260°, owing to the probable presence of impurities, and even at lower points. The presence of sulphide (see Chapter XV) might have reduced the melting point to a still lower temperature. Thus the rapidly growing dendrites would have rejected the still fluid oxide until the iron had gathered into rounded masses around which the oxide finally solidified.

Cosmic reheating.—Quite different from the foregoing structures, produced during a meteor's flight through the air, are those resulting from reheating before it reached our atmosphere. Such reheating is reflected in various alterations of structures previously established, which are not confined to a superficial zone but may extend throughout the mass.

Numerous iron meteorites show such changes of structure, varying from slight to extensive alteration. Examples of partial alteration are the Mount Sterling, Social Circle, and Dungannon octahedrites, which show a strong secondary granulation, with diffusion in dense plessite areas but with the coarser taenite lamellae little affected. More extensive change is shown in the unidentified iron illustrated in plate 67, although even in this case the octahedral pattern is clearly retained. The most complete alteration is found in some of the irons designated as nickel-poor ataxites.

Nickel-poor ataxites.—That low-nickel irons should occasionally have a structure apparently similar to that of very high-nickel irons was an anomaly not explainable by the older methods of research. Now the microscope reveals that low-nickel and high-nickel ataxites have very different structures and that there really is nothing in common between the two groups except a superficial similarity in appearance.

Experiments in the heat treatment of meteoric irons have proved that great changes could thus be produced in low-nickel irons, including the obliteration of Neumann lines and of the octahedral structure, secondary granulation, and the diffusion of taenite and phosphide.

Cosmic reheating, before the meteor arrived at the earth's atmosphere, has produced like effects, ranging from slight alteration in some hexahedrites to their complete alteration into nickel-poor ataxites. Chesterville (pl. 9) is a typical example of such an ataxite produced by cosmic reheating of a hexahedral iron, the diffusion of phosphide being conspicuous. Forsyth County (pls. 8, 9) shows similar alteration of minute phosphide bodies. An interesting feature of the latter iron is the presence of Neumann lines, showing that the alteration was cosmic, before the meteor reached the earth's atmosphere; because a degree of heat sufficient to alter the phosphide would have obliterated preexisting Neumann lines. The manner in which such reheating took place is speculative and belongs to the domain of astronomy.

In some hexahedrites superficial heating during flight has produced zones of alteration that are virtually identical in structure with nickel-poor ataxites. For example, the structure thus locally altered in the Rio Loa hexahedrite (pl. 58) and the general structure of the Chesterville ataxite (pl. 9) are virtually identical, and the granular structure of the Kendall County hexahedrite is similar to that of the Mejillones ataxite (pl. 11). Indeed it is often a matter of judgment whether a given iron should be termed a hexahedrite or a nickel-poor ataxite. Even the Neumann lines are not an unfailing criterion for, as mentioned above, they may occur in a nickel-poor ataxite, while in some hexahedrites they are so nearly absent that they might be overlooked. A cubic cleavage also would not be an infallible test, for a nickel-poor ataxite, being wholly in the alpha phase, might show such cleavage.

Considering the fact that the average composition of hexahedrites and of nickel-poor ataxites is practically identical (Farrington, 1907), and that there are abundant examples of hexahedral structure changed in zones of alteration to a condition identical with that of nickel-poor ataxites, we may assume that a nickel-poor ataxite was originally a hexahedrite. It also could be produced by reheating a coarse (low-nickel) octahedrite, and this might account for a few nickel-poor ataxites with a nickel content somewhat higher than that of hexahedrites. The scanty taenite lamellae in very coarse octahedrites might be dispersed and disappear; whereas in octahedrites of higher nickel content the lamellae are so strongly developed that even with high heating they might not be dispersed. Thus the octahedral structure would be preserved even though there might be evidence of extensive alteration. Such effects, in an incipient stage, may be observed in zones of alteration.

Cosmic thermal changes.—The fact that some meteoritic structures reflect quicker and others slower cooling, and still others reheating in various degrees, does not involve impossible assumptions as to cosmic thermal conditions.

As stated in Chapter XI, it seems unlikely that dense ataxite structures are the result of successive approaches to the sun by meteors belonging to the solar system, and it has been the prevailing view among astronomers that all meteors belong to that system. Von Nissel, however, and more recently Hoffmeister (1937) offer quite convincing evidence that many meteors have hyperbolic velocities and therefore come from without the solar system. If this view be accepted, a meteor with a hyperbolic orbit might conceivably have been reheated to any degree by a close approach to the sun or a hot star, cooling again as it receded. It is also possible that a meteor with an elliptical orbit might pass close enough to the sun to be heated sufficiently to produce structural changes if the effect were intensified by countless repetitions of such an approach.

As the conditions of production of meteors are wholly conjectural, any imaginable combination of time, temperature, and pressure may be considered theoretically possible. The author, however, is inclined to minimize the importance of such possibilities, because they could account for only exceptional structures; whereas the structures of meteoric irons are remarkable for their substantial uniformity within any given range of composition.

XIV. THE ROLE OF PHOSPHORUS IN METEORIC IRON

Of the nonmetallic elements in meteoric iron only three have appreciable influences upon its structure—phosphorus, sulphur, and carbon. Of these phosphorus is the most important. Its influence was early surmised and later demonstrated by metallographic studies. Vogel has treated this subject exhaustively in a series of contributions embodying the conclusions reached from heat treatment of meteoric irons and artificial nickel-iron alloys, the use of picrate etching (then recently developed), and interpretations of the ternary iron-nickel-phosphorus diagram. Some of his more important conclusions will later be referred to.

Schreibersite.—Phosphorus in artificial irons exists only as phosphide (Fe_3P), and in meteoric irons as the nickel-iron phosphide schreibersite—$(Fe\text{-}Ni)_3P$; or since it may often contain cobalt, $(Fe\text{-}Ni\text{-}Co)_3P$. As explained in Chapter IV, schreibersite varies in its phosphorus content, some analysts reporting ratios of Fe-Ni to phosphorus as greater than 3 to 1. Such variations may perhaps be explained on the assumption that the material analyzed was not pure phosphide but an $Fe\text{–}Fe_3P$ eutectic (p. 79).

Schreibersite usually is clear with ordinary etching, but is blackened by neutral sodium picrate. When a eutectic structure is present it may be visible with ordinary etching (pl. 59) though sometimes not (pl. 61). Kamacite with a low phosphorus content (below 1.7 percent) may be slightly darkened (pl. 57).

Picrate etching often produces a reticulated pattern on phosphide areas (pls. 55, 56, 57). This, however, does not indicate such a structure in the phosphide, but is only a stain pattern. The picrate does not actually etch the phosphide surface but merely deposits a film of stain which tends to assume a reticulated form, finer or coarser depending on whether the phosphide content in the area is higher or lower.

An interesting example of a phosphide-poor area is shown in plate 57. In this case the area showing traces of reticulation is so low in phosphide that with ordinary etching it is not distinguishable from the adjacent kamacite, but it is slightly darkened by the picrate. Possibly there might be some darkening with an even more attenuated solution of phosphide.

Phosphide in taenite.—By the application of sodium picrate to taenite Vogel (1927) established that it often contains phosphide. The latter usually shows a concentration gradient, being most abundant along the interface of a taenite body, or of the taenite border of a plessite field, decreasing inward. Taenite thus etched often shows a distinct dark border and in some cases is darkened throughout.

This is consistent with the fact that iron in the gamma phase can hold much more phosphorus in solution than in the alpha phase. Taenite, representing the gamma phase, therefore would naturally contain more than the alpha kamacite.

Schreibersite and troilite.—Schreibersite and troilite are often associated though distinctly separate, the one either adjoining or surrounding the other, or sometimes intergrown with it. The distinct separation of the two is due to the fact that they are virtually insoluble with each other in the solid state and therefore segregate in cooling. (See pl. 49.)

While pure iron sulphide melts at 1,300° the melting point is lowered if it holds iron in solution, and according to Treitschke and Tammann (1906) the sulphide-iron eutectic (Fe 84 percent, S 16 percent) solidifies at 970°. According to Stead (1900) the melting point of the iron-phosphide eutectic (Fe 89.8 percent, P 10.2 percent) is placed at 980° C. From these points downward both eutectics would progressively reject the iron in excess of the eutectic ratio, the rejection of iron from the phosphide eutectic probably proceeding the more rapidly. In meteoric irons in which troilite and schreibersite are associated, the latter sometimes surrounds the former (pl. 49), indicating that troilite solidified first.

Diffusion of phosphide.—The reheating of a meteoric iron above the melting point of schreibersite, or even to as low a point as 700° or 800°, results in diffusion of the phosphide into the surrounding area. Rhabdites thus become rounded particles or may disappear entirely, leaving only spots of phosphide enrichment, which are invisible with ordinary etching but which darken by the application of sodium picrate.

The low melting point of schreibersite and its tendency to diffuse at even lower temperatures give it an especial interest as evidence of the extent to which a given iron has undergone thermal changes. Experiments have shown that such changes are marked when an iron is heated above 1,000°, but that even as low as 700° there may be diffusion. The appearance of rhabdites with surrounding aureoles of phosphide enrichment, but still with perfect angles, is therefore an indication of incipient alteration by reheating at a relatively low temperature in the solid state.

In irons containing rhabdites or fine phosphide particles there is almost always a P-poor zone around the larger inclusions of schreibersite in which rhabdites and finer particles are scanty or absent, the phosphide in the surrounding mass having migrated to the larger bodies.

Iron-phosphide eutectics.—Needles and larger bodies of schreibersite often exhibit a eutectic structure due to the absorption of iron into solution with the phosphide. This is well shown in Río Loa, Chesterville, and Cincinnati (pls. 58, 59). Such inclusions having melted and become a liquid phosphide-iron solution, in cooling rejected the excess of iron above the eutectic ratio in the form of clear borders or droplike particles, the remainder solidifying as the Fe-Fe_3P eutectic. Thus in irons that have been reheated schreibersite inclusions usually show extensions of the diffused phosphide along adjacent grain boundaries, giving the inclusion a thorny outline.

Iron-phosphide eutectics are not necessarily a secondary product due to reheating but may be produced during the separation of the schreibersite in the gamma phase. This may be true of Soper (pl. 11) in which the abundant segregations of phosphide along grain boundaries exhibit a eutectic structure; though apparently by reason of slow cooling the excess of iron above the eutectic ratio disappeared by absorption into the surrounding area.

Ordinarily an iron-phosphorus eutectic structure is visible with ordinary etching, for although the etchant does not affect the phosphide it acts strongly along the interfaces of the phosphide particles. The structures referred to above in Cedartown and Helt Township were observed only with picrate etching; but, as stated, the exact nature of those structures is open to question.

Minute kamacite bodies in very high-nickel irons (e. g., Cowra, Klondike, Freda; see plates) often contain droplike inclusions of the eutectic, which in such cases is clearly a primary product during transformation and not a result of reheating. The examples shown in plate 55 (Helt Township and Cedartown) may have such an origin, although that conclusion is not free from doubt.

Nature of phosphide eutectics.—The absence of a eutectic structure in many phosphide areas, and its presence in varying forms in others, may perhaps be explainable on the analogy of artificial iron-phosphorus alloys.

Data on the transformations of iron-phosphorus alloys are summarized by Jordan (1939), who reproduces the diagram of Haughton (1927), stating that it is consistent with the earlier views of Stead.

According to Stead (1900) in carbon-free iron with less than about 1.7 percent of phosphorus (in the form of phosphide) a homogeneous solid solution is formed. As the content of phosphorus rises, the iron-phosphide eutectic begins to segregate, as the iron-carbon eutectoid pearlite does when carbon exceeds 0.80 percent. An example of such segregation in meteoric iron is seen in Soper (pl. 11). Similar segregations in Zacatecas (pl. 54) appear clear with ordinary etching, but might be eutectic in structure.

At about 10.2 percent phosphorus a true eutectic is formed, solidifying at 980° and resembling the structure of eutectic cast iron. Compare plate C, figure 1, with the phosphide eutectic in Cincinnati, plate 59. In the latter, and similar examples, the excess of iron (kamacite) has been rejected in droplets, the remaining groundmass being presumably about 10.2 percent phosphorus.

When phosphorus exceeds 10.2 percent in artificial alloys the excess of Fe_3P begins to be rejected in crystals resembling rhabdites. This structure has not, to the writer's knowledge, been observed in meteoric irons. At about 15.58 percent phosphorus, the composition of Fe_3P, the phosphide becomes homogeneous.

In the author's experience, with the employment of neutral sodium picrate on many irons a eutectic structure apparently was developed only once in rhabdites (Cedartown, pl. 55) and in only one or two other kinds of schreibersite inclusions (Helt Township, pl. 55). In other cases such inclusions darkened uniformly. The structure of the phosphide in Soper (pl. 11) has already been referred to. However, eutectic structures might have been revealed in other cases if the picrate etching had been done with especial care and with that object in view.

Allusion has been made to the droplike particles of phosphide appearing as inclusions within minute kamacite bodies in numerous nickel-rich ataxites (e. g., Klondike, San Cristobal, Freda; pls. 27, 28, 29). They may possibly have acted as nonmetallic nuclei in initiating the gamma-alpha transformation; or perhaps, by decreasing the solubility of nickel in their vicinity, their presence permitted the transformation to take place at a higher temperature. There appears, however, to be no visible structural difference between kamacite bodies with such nuclei and those without them.

Effects on phase transformations.—The presence of phosphorus in some cases probably influences the transformations and the resulting structures in meteoric irons, although its effects are not determinable.

By further depressing the gamma-alpha transformation (already depressed by the presence of nickel) it favors the preservation of unstable structures (i. e., transformation structures that normally disappear in slow cooling) by extending downward the range in which such structures remain unchanged. The presence of phosphorus therefore would tend to promote the development of paraeutectoid structures in nickel-rich ataxites, as will presently be explained.

Genesis of phosphide inclusions.—Vogel's conclusion that droplike masses of schreibersite originate from the melt, while rhabdites and needles separate in the solid (gamma) state, seems to be fully sustained by the ternary iron-nickel-phosphorus diagram, by the results of heating experiments, and by the habits of the various types of inclusions. The segregations of needles (lamellae) in the gamma phase would naturally be interrupted if a permanent octahedral structure were formed; therefore we find long needles confined to hexahedrites and nickel-poor ataxites. In such irons the gamma-alpha range was narrow and at a high temperature, and the resulting octahedral structure was incipient and transitory, causing only a temporary barrier to the formation of such lamellae. This seems evident from the preservation of lamellae of exceeding fineness and regularity, as in Walker County (pl. 52).

The orientation of phosphide needles usually seems unrelated to the Neumann lines in hexahedrites or the Widmanstätten pattern in octahedrites. They are, in fact, necessarily unrelated; for the planes on which precipitation occurs are determined by the crystalline habit of the precipitant, not by that of the matrix, and in an artificial iron-phosphide solution the phosphide separates on planes that are neither cubic nor octahedral. Therefore the orientation of a phosphide needle (lamella) may or may not coincide with some plane of an octahedrite, or with any of the twinning planes developed in the alpha phase which are evidenced by Neumann lines in hexahedrites.

Brezina (1894) from a study of the schreibersite lamellae in certain octahedrites concluded that they follow dodecahedral planes. That conclusion, however, seems clearly erroneous (p. 64).

Phosphorus and plessite.—Phosphorus has some influence on the formation and the structure of plessite, though its role is variable and in most cases not important.

Inasmuch as the kamacite and taenite in octahedrites are relatively phosphorus-poor, the phosphide content of the original melt is correspondingly concentrated in the plessite fields. The effect of such enrichment, however, is chiefly cumulative, tending more or less to further depress the gamma-alpha transformation, already lowered by the presence of nickel. Inasmuch as dense or eutectoid plessite represents a gamma-alpha transformation structure, produced at low temperatures where diffusion is retarded, any admixture of phosphorus would depress it still further, and thus prolong transformation to a point where the resulting structure would be still finer.

Phosphorus thus tends to promote eutectoid structures in artificial irons containing carbon. A very small percentage of phosphorus gives rise to small segregations of an iron-phosphide or iron-phosphide-carbon eutectic—the latter known in artificial irons as steadite. According to Stead, such a eutectic can be detected in cast iron containing only 0.03 percent of phosphorus.

It is to be noted that the tendency of phosphorus to produce eutectoid structures in artificial irons increases with the nickel content. Thus with pure iron 0.80 percent of carbon is required to make a completely pearlitic (eutectoid) steel; but with 8.7 percent of nickel only 0.50 percent of carbon is required, and with 13.20 percent of nickel only 0.10 percent of carbon.

These facts are of interest in connection with an occurrence of steadite in an inclusion in meteoric iron, referred to in the following chapter.

Studies on the Cape iron.—Vogel (1927) in experiments upon the Cape of Good Hope iron (Ni 15.67 percent, Ni-Co 16.62 percent) found that the structure designated by him as eutectoid (termed by the author paraeutectoid) is stable up to 700°—that is, it is not altered by heating—but that a sample heated to 1,450° and quenched showed a characteristic gamma granular structure with twinning; that when further heated seven hours at 700° and quenched it showed a structure of polyhedral alpha grains without twinning; and that on further heating for 25 hours at 650° it again became eutectoid. From these facts he deduced that the structure expresses the structural equilibrium of a ternary iron-nickel-phosphorus alloy with 0.2 to 0.3 percent of phosphorus, a product of slow cooling, either from the original melt or after reheating above 1,000°.

It is not necessary, however, to ascribe the structure either to the action of phosphorus or to reheating, because the diagram (fig. 5) indicates that the changes thus produced in the Cape iron should be approximately the same even if no phosphorus were present. In fact, the latest analysis of that iron, by Fahrenhorst in 1900, gave it only 0.09 percent of phosphorus. Even in the absence of phosphorus, in an iron-nickel alloy with as much as 15 percent nickel the transformation would take place below 400°, at which temperature diffusion has practically ceased. Therefore, such a structure as that of the Cape iron would be stable above that line and might be preserved to ordinary temperatures, even if cooling were very slow, because of the rigidity of the mass.

The phosphorus content of the Cape iron is slight from the metallographic standpoint. Other high-nickel ataxites with similar structures contain as little, or even less (e. g., Deep Springs 0.06 percent, Iquique 0.05 or 0.07 percent, Illinois Gulch 0.07 percent, Guffey 0.02 percent), and sodium picrate etching reveals no phosphide in them.

References.—The relationships of phosphorus with iron, nickel, and sulphur, and the resulting structures in artificial and also in meteoric irons, have been treated exhaustively in the contributions of Vogel and his collaborators. Those who wish to pursue the subject further are referred to the publications of Vogel (1927, 1932, 1938), Vogel and Tonn (1930), Vogel and DeVries (1931), and Vogel and Bauer (1931), the titles of which will be found in Literature Cited.

XV. CARBON AND SULPHUR IN METEORIC IRON

Martensite and troostite.—Quantitatively carbon is a very minor constituent in meteoric irons, appearing only in fractional percentages and in most analyses not at all. When present it is practically always in the form of inclusions, either of graphite or of the carbide cohenite, which were discussed in Chapter IV. Except for two small areas of exceptional character, the author has observed no instance of iron-carbon structures analogous to those produced artificially.

Some writers, however, have alluded to supposed iron-carbon structures in meteoric irons, and Vogel (1927) reported and illustrated an example of what he termed martensite or troostite in Casas Grandes. That iron contains 0.177 percent of carbon, of which 0.145 percent is in combined form. The latter percentage would represent 2.175 percent of carbide, which in theory might make possible a local development of martensite or troostite as reported by Vogel. The author, however, regards the structure referred to not as an iron-carbon but as an iron-nickel structure.

The presence of carbon would have the same general retarding effect upon the gamma-alpha transformation in natural nickel-iron alloys as it has in artificial ones. As may be seen by the iron-nickel diagram, however, the presence of nickel greatly lowers that point; with 10 percent nickel it is depressed to 400°, and with about 25 percent to room temperature. Martensite is produced by rapid cooling from the Ar_3 point (Chapter VII). Thus its preservation would theoretically be possible in areas of carbon enrichment in octahedrites with 7 percent or more of nickel.

The author believes, however, that the few examples of supposed martensite or troostite cannot be accepted unreservedly. As was mentioned in Chapter VII, acicular transformation figures consisting of alpha and gamma needles suggest a martensitic structure, and black unresolved alpha-gamma aggregates resemble troostite or sorbite. Apparently the structures referred to by Vogel were not verified positively by tests for carbide.

Instances of Fe-C structures.—The author has found only two examples of unquestionable iron-carbon structures in meteoric irons. One of these was found in an inclusion of extraordinary character in Locust Grove (pls. 65, 66).

The inclusion consists mainly of a rather coarse dendritic mass in which light gray dendrites appear, surrounded by white areas, all in an almost black groundmass appearing like troostite. Etching with alkaline sodium picrate leaves the gray dendrites unaffected, showing that they consist of a gamma-alpha aggregate. The clear white areas darken, indicating the presence of phosphide.

The question remained whether the black areas represent merely a phosphide-iron solution or whether they also contain carbon. That was determined by examining an unetched surface on which the component that appears white in plate 65, figure 2, and black in figure 3 is visible, with a gray color similar to that of graphite inclusions in artificial irons. The gray dendrites and the dark mottled groundmass appear white and structureless, which is consistent with the assumption that they are wholly metallic (gamma-alpha) and therefore would show no structure without etching. It would seem fairly certain, therefore, that the matrix of the dendrites consists of the iron-phosphorus-carbon eutectic known as steadite in artificial irons (Fe, Fe_3P, Fe_3C). A very small proportion of carbon is sufficient to produce visible segregations of steadite in artificial irons containing as much as 0.03 percent of phosphorus.

This conclusion is substantiated by the demonstrable presence of carbide in a narrow zone of acicular appearance surrounding the dendritic area (pl. 66). When this is etched with nital it shows a precipitation of a white substance along crystallographic planes, and also along grain boundaries, suggesting in appearance the structure sometimes found in hypereutectoid cast steels in which free cementite is rejected partly in the form of oriented needles on crystallographic planes and partly to the grain boundaries.

That such is also the structure in this case is proved by etching with alkaline sodium picrate, a common test for cementite in artificial irons. The white component is now blackened, proving it to be cohenite (cementite). The structure resembles that found in a 3 to 5 percent nickel carburized steel and seems beyond question to be identical in nature.

The composition of Locust Grove is consistent with the foregoing conclusions, as it contains 0.02 percent carbon and 0.18 percent phosphorus. The inclusion evidently marks a spot of local enrichment in which the percentages of either or both were higher than the above averages for the mass.

A second example of an iron-carbon structure (pl. 66) was found in Chesterville—like Locust Grove, a nickel-poor ataxite and with approximately the same composition. At the center of a spot of carbon enrichment is a rounded area that is substantially identical with a white phosphoretic cast-iron, dendrites of a pearlitic nature in a white groundmass of steadite. This is surrounded by an area of dark pearlitic grains with white ferrite (kamacite) along their boundaries, the equivalent of a steel with about 0.55 percent carbon. Farther from the center this gives place to a lighter granular structure, the equivalent of about a 0.25 percent carbon steel, in which the ferrite (kamacite) predominates.

This unique structure may have been due to the presence in the original iron (before the heat alteration which turned it into an ataxite) of a body of cohenite enriched with phosphorus in the form of schreibersite inclusions, thus making possible the production by fusion of an iron-carbon structure and also of a limited amount of the eutectic steadite.

Of three analyses of this iron by Sjöström (in Cohen, 1908) two showed 0.34 percent phosphorus and 0.02 percent carbon; one of the three showed no phosphorus, and one no carbon. The variations apparently were due to the presence or absence of cohenite or schreibersite in the samples analyzed.

Origin of such structures.—It is to be noted that the only two irons in which any kind of iron-carbon structures were found are nickel-poor ataxites, probably formed by the strong reheating of a hexahedral iron which happened to contain inclusions of cohenite, followed presumably by relatively rapid cooling. Thus the conditions of production would in some measure resemble those of artificial irons, where the rate of cooling is too rapid for the segregation of cementite.

With annealing the pearlite in artificial iron breaks down, the cementite segregating in spheroids (pl. C), but with the utmost attainable slowness of production, such particles are minute and thickly dispersed. In normal meteoric irons, on the other hand, the cooling was probably of secular slowness; and thus it was possible for the carbide to segregate completely in relatively large and scattered cohenite crystals, and no pearlite remained, even though the average content of combined carbon might have been such as to produce some pearlite under artificial conditions.

Ferrous sulphide.—Sulphur in meteoric irons occurs chiefly as troilite. Though not an appreciable factor in the general structure, it nevertheless presents interesting features.

The iron-sulphide (Fe-FeS) constitution diagram worked out by Treitschke and Tammann (1906), of which an illuminating discussion is given by Rinne and Boeke (1907), shows transformations similar to those of iron, with gamma, beta, and alpha phases. The pure sulphide melts at 1,300°. The melting point of the iron and iron-sulphide solution (or its point of solidification) varies according to its proportions. The eutectic temperature for a solution of 84 percent iron and 16 percent sulphide is 970°, which also marks the gamma-beta transformation. The beta-alpha transformation takes place at the very low point of 130°.

Age of troilite inclusions.—The conclusion of Rinne and Boeke was that the iron-bearing sulphide separated from the melt in minute droplets, consolidating into the larger droplike or nodular forms in which troilite most commonly occurs, from which as cooling proceeded the dissolved iron was progressively rejected. Even apart from the diagram, it is clear that such inclusions are an original segregation from the melt, because they are independent of the Widmanstätten structure and therefore obviously older. As cooling proceeds the troilite masses continue to reject more and more nickel-iron in the solid state, which produces the band of "swathing kamacite" that usually surrounds such inclusions when they are of any considerable size, against which the octahedral structure abuts unconformably.

The eutectic temperature of iron and troilite (970°) is 300° to 500° above the beginning of the gamma-alpha transformation in an alloy in the composition range of octahedrites. Thus the troilite necessarily would have solidified before the production of the octahedral structure began. At 970° the nodules would be iron 16 percent, sulphide 84 percent. But inasmuch as the saturation point of sulphide in alpha iron is stated to be only 2 percent, most of the iron in the eutectic would be rejected as it cooled from 970° to room temperature; in effect the nodule as it shrinks leaves behind it a thickening skin of kamacite.

In its final form the analyses indicate that troilite contains 3 to 4 percent of iron in solid solution. This proportion, somewhat higher than the above-mentioned saturation ratio of 2 percent, might be due to the presence of iron in the form of occluded particles rejected along grain boundaries in the troilite and not actually in solid solution.

In their discussion of the ternary iron-nickel-sulphide system, Vogel and Tonn (1930) also reach the conclusion that troilite, both in droplike form and crystals, can have separated only from the liquid state. The same conclusion applies to Reichenbach lamellae.

Reichenbach lamellae.—The fact that Reichenbach lamellae (Chapter IV) are oriented according to cubic planes is not readily explainable from the iron-sulphide and iron-nickel-sulphide diagrams, except upon the assumption that they separated in the delta phase, which like the alpha phase is cubic in its crystallographic planes. Their separation obviously must have been complete long before the gamma-alpha transformation began, because even the very fusible iron-iron-sulphide eutectic solidifies at 970°; whereas the gamma-alpha transformation, even in the lowest nickel octahedrites, did not begin until about 700°.

The hexagonal crystals observed in a few irons also probably separated in that phase, slow cooling through the higher temperature range affording time for them to perfect their crystalline form.

Troilite has a structure of polyhedral grains, similar to that of ferrite and nickel-iron in the alpha phase (pl. 49).

Expansion of troilite.—The very considerable expansion of troilite at its beta-alpha transformation at 130°—sufficient to burst porcelain tubes used in experiments with the artificial sulphide—is cited by Rinne and Boeke, and also by Vogel and others, as a possible explanation for the disruptions evidenced by cracks often observed in meteoric irons. To the author such cracks seem adequately explainable upon other grounds (see Chapter XVI), apart from the fact that they occur in irons that contain no troilite.

Swathing kamacite.—The character and occurrence of swathing kamacite were mentioned in Chapter III, and in this chapter it has been referred to as being rejected from cooling and shrinking masses of troilite. That mechanism seems to explain quite satisfactorily the bands surrounding nodular masses. The fact that they are likely to vary in thickness according to the size of the nodule, and are lacking around small inclusions, is also consistent with that explanation.

We find, however, that thin needles (lamellae) of troilite in some octahedrites, especially Reichenbach lamellae, are sometimes surrounded by broad zones of kamacite, unrelated in direction with the structure of the mass but having angular outlines not exactly corresponding with those of the lamellae. Their thickness may be much more than that of the lamellae, which would preclude the assumption that they were wholly a product of rejection from the latter during cooling. In such cases a narrow band of rejected kamacite may have acted as a nucleus for the precipitation of additional kamacite as the Widmanstätten structure developed.

Swathing kamacite also is found surrounding needles of schreibersite (pls. 3, 51), the needles themselves showing no iron-phosphide eutectic structures, which would be present if the kamacite had been rejected from an iron-phosphide liquid solution.

In such cases the only explanation would seem to be that such nonmetallic inclusions served as nuclei around which the gamma-alpha transformation was initiated and a more copious separation of the kamacite was promoted. Such a process might also account for the fact that in many ataxites small kamacite bodies often enclose minute cores of iron-phosphide eutectic.

XVI. NEUMANN LINES AND DEFORMATIONS

In both meteoric nickel-iron and in the ferrite of artificial irons fine parallel lines are often observed which are called Neumann lines, so named after J. Neumann, who discovered them in 1848 in the Braunau hexahedrite.

In artificial irons they are commonly designated by metallographers as Neumann bands, but in the literature of meteorites they have been uniformly termed lines ever since their discovery. Neither term exactly describes them, because both in natural and artificial irons they may appear as exceedingly fine lines or as double lines or bands of varying width. In this work it seems best to retain the original designation, in conformity with the practice of writers on meteorites.

Occurrence.—In ferrite, which is granular, the lines are parallel in each grain but diversely oriented in different grains. Sometimes a grain shows more than one set of lines. The same is true of granular meteoric irons in most cases. In hexahedrites grains are often absent, and there is a homogeneous or unigrain condition not found in artificial irons; therefore the lines, not interrupted by grain boundaries, may be parallel throughout the mass. They often are visible to the eye on an etched surface.

In octahedrites Neumann lines appear, often conspicuously, in the kamacite bands. In octahedrites they are identical with those in hexahedrites, but they usually are interrupted by taenite lamellae so that adjacent kamacite bands have different sets of lines. Exceptionally they run across several bands with little or no interruption or change of direction. In the grains of granulated kamacite bands they usually are diversely oriented, and the same is true of many granular hexahedrites. Often, however, they run without change across a number of grains in hexahedrites and also across the large grains in some of the coarser octahedrites.

It has been stated that Neumann lines are not found in ataxites; yet exceptionally they are present in nickel-poor ataxites, as in Forsyth County (pl. 8). This iron presents a homogeneous mass of kamacite containing minute phosphide particles but with no structure that would interrupt the formation of Neumann lines. As pointed out in Chapter XIII, there is no definite demarcation between hexahedrites and nickel-poor ataxites.

In artificial irons Neumann lines occur only in ferrite, and in meteoric irons only in kamacite. They are absent in nickel-rich ataxites, which are composed of an exceedingly fine mixture of kamacite and taenite.

Sometimes there is only a single set of parallel lines, but, especially in hexahedrites, there often are two or more sets. It has been established that the lines are formed along the (211) alpha, a 12-family plane, or in other words are parallel with the planes of the trapezohedron, so the lines might develop in any number of directions up to twelve. Three or four sets are common, and occasionally five or six are observed. In Scottsville (pl. 4) traces of a seventh can be recognized. The lines are usually straight, often of the most perfect regularity, but sometimes they are irregular or distorted.

Neumann lines and slip bands.—In artificial irons, where the effects of deformation have been minutely studied, a distinction is drawn between Neumann lines and slip bands. The latter (termed by some writers, perhaps more aptly, slip lines) appear as very fine black lines on the polished surface of metal that has been subjected to strain, and which disappear with repolishing and etching, while Neumann lines persist. Slip bands are caused by a slight movement along gliding planes. Neumann lines are produced in artificial iron most readily by shock or sudden stress, though they may also result from strain.

Origin.—The most generally accepted view is that slip bands are produced by gliding, but that Neumann lines are mechanical twins; though Rosenhain and McMinn (1925) take the view that they are not twins but the result of local deformation from rapid heavy stress. In New Baltimore (pl. 76), where there is abundant evidence of shearing displacements and other movements, the lines follow the planes of such deformation. They are very irregular in places, conforming with the movements of the metal.

Neumann lines produced in artificial iron by the action of explosives are illustrated in a large number of photographs by Foley and Howell (1923) and Foley and Crawshaw (1926). As in meteoric irons, sets of fine and coarse lines appear in the same grain, each set being uniform in character. Lines were produced in three directions within one grain, and in a few instances in four directions.

We may therefore assume that in meteoric irons Neumann lines may be the result either of stress or shock. Whether they are faint or strong, sparing or abundant, and whether there is one set or several, are conditioned by the strength, direction, or suddenness of the deforming force, and also no doubt by the structural properties of the iron. That one set of lines should be very fine while another in the same area is broad would be consistent with such a genesis. The occasional exaggerated breadth of a given set, usually with irregular or wavy boundaries, would naturally result from the section's having been made at an angle oblique to the twinning plane; whereas if made at right angles to it, the lines would appear finer and more sharp-cut (pl. 7).

Differences in the prominence of different sets of lines may also in some cases be due to the more active attack of the etchant along certain planes than along others. According to Stead, cubic planes are more resistant than octahedral planes.

Smith and Young (1939) suggest that slip planes are due to differential contraction in cooling and to expansion stresses caused by an increase in volume at the point of the gamma-alpha transformation. Neumann lines, however, are readily produced in cool, or cold, artificial iron; and the fact that they are found in Forsyth County and Dungannon, which apparently were reheated strongly enough to obliterate any previously formed lines, would indicate that they arise at temperatures below the point of the gamma-alpha transformation.

Resemblance to gamma twinning.—The appearance of gamma grains due to twinning in a high thermal range, though somewhat resembling Neumann lines, is different in character. The gamma grains in artificial iron are marked by profuse twinning. It has been suggested that this might be due to stresses caused by sudden increase in volume at the point of the gamma-alpha transformation, but heat etching in the gamma phase has proved the existence of the twinning structure in that range.

Neumann lines in artificial iron are produced only in alpha ferrite, the more readily the cooler the metal is. In meteoric irons they occur only in alpha kamacite.

Manner of formation.—The Neumann lines in meteoric iron are clearly the result of stress or shock in the alpha phase, like those produced in that manner on a microscopic scale in the grains of ferrite.

In the literature of meteorites little is found regarding the nature or origin of the shock or stress whereby the Neumann lines could have been produced. To the author the most probable cause would seem to be the violent stresses caused by atmospheric pressure during flight. This is discussed later in this chapter.

As pointed out by Rosenhain and McMinn (1925) the tendency of a blow is to concentrate the slipping in a few broad bands, while gradual deformation distributes it over a number of planes. Thus

Neumann lines produced by explosions are usually in one direction. In meteoric irons the numerous sets are consistent with deformation by air pressure, which although rapid would be less so than by the action of an explosion or a blow.

Thermal alteration.—Neumann lines are very susceptible to alteration by heat; in fact they afford the first visible evidence of change upon heating within the higher alpha range. The lines begin to widen and become distorted, merging into the developing grain boundaries, until they disappear in the completed secondary granulation. Experiments by Kasé (1925) on samples of Sacramento Mountains (nickel 8.7 percent) showed that with prolonged annealing even at as low a temperature as 550° to 560° the lines are ultimately obliterated. It has been stated by Tammann (1923) that they disappear slowly with prolonged heating even at 400°.[5]

The presence of perfect Neumann lines therefore indicates that the iron has not been much reheated, either during atmospheric flight or artificially. It may, however, have been reheated cosmically, the lines having been produced after the alteration. In the case of Forsyth County, previously mentioned, in which Neumann lines are present, the diffusion of phosphide particles indicates cosmic reheating. In Dungannon, an iron that has been markedly altered by reheating, the presence of Neumann lines in some areas proves that the alteration was cosmic and the lines were produced subsequently; for the degree of reheating that was required to produce the alterations in structure would have obliterated any previously existing Neumann lines.

The fact that the lines are absent in zones of alteration would indicate that when they are present in the interior of the mass they were not produced by impact upon the earth. If they were produced by impact, there seems to be no reason why they should not be formed within the zone of alteration, which in most cases would be quite cool when the meteorite struck the earth.

When a sample of meteoric iron shows Neumann lines in some areas but in others gives evidence of reheating by the diffusion of phosphide, it is likely that the latter area is part of a zone of alteration, even though the sample may not include any part of the original surface of the mass. As schreibersite melts at 970°, and does not even begin to diffuse below about 700°, no great change in phosphide inclusions would be possible without the alteration or obliteration of Neumann lines.

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[5] Two exceptional cases are mentioned by Foley and Howell in which Neumann lines proved resistant to temperatures that have been regarded by all authorities as sufficient to obliterate them. One investigator, they report, heated a sample of artificial iron to 1,000 centigrade (sic) and cooled it slowly, and another held a sample at that temperature for 30 days, both stating that the lines remained. As these results are so greatly at variance with the experience of many investigators, it is hard to believe that some unknown factor may not have influenced the results.

"False" Neumann lines.—Despite the fact that the appearance of Neumann lines is so characteristic, certain structural appearances of very different origin may sometimes be mistaken for them. That is especially true in kamacite showing a gamma-alpha transformation structure, which may show striations that at moderate magnification resemble indistinct, and even fairly clear, Neumann lines. Examples are illustrated in plate 35. With high magnification the illusion is quickly dispelled, the nature of the structure being apparent.

Very fine oriented needles of schreibersite, as in Walker County (pl. 52), might also have such a resemblance.

Deformations.—Some meteoric irons bear evidence of deformations subsequent to the establishment of their structure, varying from large cracks or complete disruption down to very minute displacements.

Microscopic displacements have been observed by various investigators. An outstanding example is El Inca (Tamarugal) described by Rinne and Boeke (1907), in which a troilite nodule was broken in two, and one half slid past the other. Helt Township shows dislocation of taenite lamellae (pl. 76) and similar appearances have been described in Puquios by Brezina (1895) and by Cohen (1905) in Chesterville. Striking examples of displacements are found in Canyon Diablo (pl. 75) and New Baltimore (pl. 76).

Causes of displacements.—Various causes have been suggested for such displacements, the most frequently mentioned being the shock resulting from the impact of the mass upon the earth. Rinne and Boeke make that suggestion in the case of El Inca. They also mention possible cosmic causes, as well as the disruptive force developed by the expansion of troilite at its beta-alpha transformation, which takes place at 130°, pointing out that cracks have been observed near large troilite inclusions.

The last explanation is clearly inapplicable to the case of El Inca, because the marked displacement of the two halves of the troilite nodule shows that it was broken by an outside force. In any view, the expansion of a troilite nodule would be small in comparison with the bulk of the surrounding iron, and it would be exerted equally in all directions; so as a disruptive agency it would be negligible. Moreover, displacements—to the extent of wide cracks and fissures—are found in irons containing little or no troilite.

The shock of impact also is an unsatisfactory explanation, because often the impact is not violent. In the case of Helt Township, for example, the small mass fell with so little force that it only slightly buried itself in soft earth.

In New Baltimore (pl. 76) the extensive distortion seems to be the result of stresses greater than would likely have been produced by impact upon the earth. It cannot be disproved, of course, that deformations and disruptions may not have taken place outside of the earth's atmosphere. The pressure of the air during flight, however, is of such extreme intensity that the resulting stresses would seem to be sufficient to account for such phenomena. The action of the air in such circumstances is comparable in intensity (though not in suddenness) with that of a charge of high explosive, resulting sometimes in the production of large fissures and even in the complete disruption of the mass.

Evidence of air pressure.—This conclusion is supported by direct evidence in the case of iron meteorites (e. g., Pitts), that give clear proof of having broken in the air. The fragments of Pitts, which were observed to fall, have surfaces furrowed and sculptured by heat and air pressure during flight, and also freshly fractured surfaces showing no alteration; thus proving that disruption occurred after the flight through the air had been partly completed. Stony meteorites afford many such examples, fragments showing surfaces in all stages from a heavy fusion crust to a slight scorching, or a freshly broken and unaltered surface.

In lenticular masses that traveled flatwise through the air (e. g., Seneca Township, Wood's Mountain), the author (1939) found the cracks to be almost entirely in the peripheral portions and to enter the mass only on the rounded side that was foremost in flight—the pressure tending to bend backward the thinner peripheral portions and thus cause the mass to open on the forward side, but to compress the rear side where no cracks appear.

The example of Helt Township is of interest because the partial granulation produced by heating during flight through the air was evidently contemporaneous with or subsequent to the displacements, thus proving that the latter could not have been caused by impact.

XVII. METALLOGRAPHIC TECHNIQUES

Though metallography utilizes many methods of chemical and physical research, it is impracticable in this chapter to do more than give an outline of those found most useful in the study of meteoric irons. These include the preparation of specimens, macroexamination, microexamination, photography, and the identification of components by chemical tests, the spectroscope, X-ray analysis, and other methods.

Specimens for study.—Meteorites of any type are so rare that it is difficult to obtain specimens except by purchase from a reliable dealer. Small samples are usually sufficient and are much more convenient than large ones. In the case of octahedrites, because of their coarse and varied structures, surfaces of a few square inches are desirable; but very small samples of hexahedrites and ataxites are often sufficient.

The most convenient form is a slice, which preferably should be of uniform thickness so that the surface may be level on the microscope stage. For use with a metallographic camera where the specimen lies on the stage with its polished face downward, the shape is immaterial.

Macroexamination.—While the greater part of metallographic study is done with the microscope and camera, at moderate to high magnification, macroexamination—by the eye, with a hand glass, or with a microscope at low power—is of great importance.

Only the coarser structures are thus observable, but these should be carefully studied as a preliminary to the more minute examination. Thus the presence and character of visible inclusions should be noted. Most of them are soon recognized easily, but it may be necessary to verify their nature by their hardness, by sulphur printing, or other tests.

In octahedrites the characteristic structure often can be seen only with the unaided eye and on a fairly large surface. When the structure is coarse and faint it might escape observation under the microscope. The sheen of kamacite also, even when strong to the eye, often is not observable on the very lightly etched surfaces employed at high magnification.

Preparation for macroexamination.—The preparation of a specimen for macroexamination involves the preliminary steps in preparing it for microexamination and photography. These are as follows:

1. *Obtaining a flat surface:* This may be done with a hacksaw (automatic if possible) or, if available, by a power-driven steel band fed with emery and water such as some museums and laboratories possess. An emery disk may be used for cutting when the iron contains silicate inclusions. When a specimen is to be examined without removing a slice, a flat area of suitable size may be produced on a carborundum wheel, care being taken that it is not unduly heated.

2. *Polishing:* The plane surface is conveniently smoothed on coarse emery paper or cloth, or on the side of a carborundum wheel. A round piece of emery paper may be applied (without adhesive) to a disk of wood or metal mounted on a grinding machine. The coarse emery paper is followed with finer grades up to No. 0 or No. 00 metallographic emery paper, or its equivalent, each time care being taken to remove all scratches left by the preceding coarser paper. The polish is now sufficient for macroetching, although under high magnification the surface would appear so rough that fine structures could not be seen.

Under no circumstances should buffing be employed, as it produces a superficial dragging of the metal.

Macroetching.—Macroetching, which is much deeper than that used for microscopic work, may be done with a variety of etchants. Nital (5 percent nitric acid in alcohol) is most satisfactory, as it does not cause the discoloration around troilite inclusions which takes place if an aqueous solution of the acid is used. When the iron is free from troilite 5 to 8 percent of nitric acid in water is satisfactory. The author has used with good results ammonium persulphate (2 grams to 10 cc. of water, freshly prepared).

The etchant is best applied with a soft brush (an old shaving brush serves well); it should be spread plentifully and evenly over the surface and kept constantly in motion, until the maximum distinctness of structure is developed. Very thorough washing under a stream of water, preferably warm, is necessary to avert rust which often forms in a short time—particularly if the iron contains cracks or interstices. The specimen should then be dried and preferably kept warm for some time.

If a specimen is to be kept for any considerable time after macroetching, the surface should be covered with a thin coat of lacquer or spar varnish. Until thus protected, it should not be touched by the fingers, else stains are likely to be produced.

When a specimen is to be macroetched for permanent display, using nitric acid and water, it is advisable to fill any cracks or interstices with shellac before etching, to prevent the penetration of acid into the mass. This, however, cannot be done if microetching is to be done later, because the alcoholic etching solutions would dissolve the shellac.

Macro-observation.—The macroetched surface should be examined with a hand glass or under a microscope at low magnification (10 to 25 diameters). If it is an octahedrite, the width of the bands may be measured with an eye-piece micrometer. If a hexahedrite, the character of Neumann lines, grain boundaries, etc., may be noted. Inclusions of schreibersite or of cohenite are easily identified by their resistance to a needle scratch, although the one is not easily distinguished from the other.

Troilite inclusions can be located and identified by a sulphur print, which is best taken after polishing and before etching. Troilite may thus be distinguished from graphite, which does not show on a sulphur print; it is often associated with troilite and might escape observation. If the sample includes part of the natural surface of the mass, the surface should be examined at its edges for possible intrusions of magnetic oxide or invasions of hydroxide.

Finally, the specimen should be photographed with ordinary daylight or oblique light, either natural size or at low magnification (5 to 10 diameters). A photograph at low power is especially desirable for reference and comparison with later photomicrographs, and often aids in their interpretation. In finest octahedrites, for example, it is difficult sometimes to judge at 100 magnification whether a given structure is a kamacite band or part of a plessite field.

Micropolishing.—After macroexamination is finished, the specimen is ready to be further prepared for microscopic study.

1. The surface, roughened by the macroetch, should again be brought to as good a polish as before.

2. Polishing is continued on metallographic emery papers of increasing fineness, from 0 to 000, which may be obtained from dealers in laboratory supplies. In the author's opinion, the best results are obtained by hand, after the first rough polishing—by laying the paper on a sheet of plate glass or other hard even surface, rather than by using paper mounted on revolving disks. The specimen should be rubbed to and fro with gentle pressure and not too fast, and in a straight line so that the scratches are all in one direction. On changing to a finer paper, the rubbing should be done at right angles to the previous scratches and continued until they are all removed.

3. The final polish is given with jeweler's rouge, used wet on a revolving disk covered with billiard cloth. Formerly the rouge was used in the usual solid form, the powder incorporated in a greasy vehicle, but a more convenient powdered form is now available. Alumina powder, prepared especially for the purpose, is preferred by some. This fine polishing also can be done by hand, but much more conveniently on machines made for the purpose with horizontal revolving disks, with which metallographic laboratories are equipped.

After the finest possible polish seems to have been obtained, the surface of the sample should be examined under a microscope at 100 diameters, and if imperfections are found they should be removed by further use of the rouge. It is then advisable to etch the surface very lightly (picral or nital 5 seconds) to remove any traces of cold working (dragging of the surface by the abrasive) and then repolish lightly with the rouge.

4. The specimen should then be thoroughly washed in a stream of water and dried in the air—conveniently before a fan, or if in a laboratory by an air blast; never by wiping or blotting. It may then be rubbed very lightly once or twice on a piece of chamois skin stretched over a smooth surface and perfectly free from dust, to remove any trace of deposit from the dried film of water. If it is not to be etched immediately, it should be placed in a desiccator until needed.

The foregoing is only a general outline of the technique of polishing, which varies in practice according to individual preferences. Further information can be found in textbooks on metallography, and instruction by someone skilled in such work is still more helpful.

Microetching.—Before the surface is microetched it should be examined under the microscope for nonmetallic inclusions—such as graphite, silicates, and oxides—that are visible without etching. Schreibersite and cohenite, though showing no contrast in color, are usually visible because of their being slightly in relief. The revelation of such structures in this way without etching, because of variations in hardness, is sometimes referred to somewhat inaptly as "relief etching."

The etchant is best applied with absorbent cotton gently wiped over the whole surface; the progress of the attack should be closely watched, as it is much faster on some irons than on others. Previously the specimen should have been washed with benzole or acetone, applied with cotton, to remove any trace of grease in case the hard form of jeweler's rouge was used in polishing. If the powdered form was used, washing in water is sufficient. When etched the surface should be thoroughly washed in a stream of water, dried before a fan or air blast, and placed in a desiccator.

The time of etching depends upon the etchant and upon the magnification to be used. For most meteoric irons the time of etching is short, especially for examination or photography at high magnification. With picral etching, which the author has found most generally useful, the time varies from 3 to 10 seconds for high magnification (1,000 or more). It may be from 30 to 80 seconds, sometimes more, for work at 50 diameters. These limits are only approximate, varying according to composition and structure.

A convenient procedure is first to give the specimen a very light etch for work at high magnification; then somewhat more for photography at 250 to 500 diameters; and finally for moderate or low magnification a still stronger one. If the stronger etch is given first, it is necessary to repolish the specimen for the light etch required for high magnification. It should always be borne in mind that the results of etching, even with an apparently uniform technique, are not invariable; so when peculiar or unexpected effects are noted, the process should always be repeated to guard against unsound conclusions.

Etching reagents.—In the study of artificial irons a great variety of etchants have been used, which may be found in textbooks. With meteoric irons, however, the following list includes all that would ordinarily be employed:

Picral (5 percent picric acid in alcohol) and nital (5 percent nitric acid in alcohol) are most commonly used, of which the former is preferred by the author for all ordinary work. It develops the structure the same as nital, but its action is slower, and therefore the operation is more controllable. It also does not cause stains to run over in very fine structures, which sometimes occurs with nital etching.

Nital, however, occasionally works better on individual irons or on particular structures. A mixture of picral with 10 percent to 50 percent of nital also has been found to be the most satisfactory etchant for certain details of structure.

Nitric-acetic acid (equal parts of concentrated nitric acid and glacial acetic acid) is used on high-nickel steels and has proved useful on a few nickel-rich ataxites that revealed little or no structure with ordinary etchants.

Ferric chloride ($FeCl_3$ 5 grams, HCl 50 cc., alcohol to make 1,000 cc.) is considered effective in developing etching pits and Neumann lines in artificial irons. Its usefulness with meteoric irons is minor.

Stannous chloride, used on artificial irons to show oxide, is also of minor value because such inclusions are visible on an unetched surface.

A number of reagents used with artificial irons (such as Stead's, Le Chatelier's, Rosenhain and Haughton's) depend for their effect upon the selective deposition of a film of copper. The author has not found them useful. They are employed chiefly for revealing the presence and variations of phosphorus content, which in meteoric irons is more satisfactorily shown by etching with neutral sodium picrate.

Ammonium persulphate (10 percent by weight in water, freshly prepared) is recommended strongly by some technicians for bringing out grain structures and other details in artificial irons, with a lighter attack than is needed with other etchants. The author has used it with fair results in most cases, but the surface is apt to appear clouded with minute specks and fine structural details are less clear than they are with picral or nital etching.

Observations on etching.—The structural details and inclusions in artificial irons are very much finer than in meteoric irons, and therefore some etching methods that are necessary with the former are not so with the latter. The same reagent is often effective on meteoric irons with a much shorter application than is required with artificial irons—e.g., etching for carbide with boiling alkaline sodium picrate.

As the attack of any solvent etchant is strong along the interface of an inclusion, the appearance of very minute inclusions in artificial irons may not appear consistent with that of similar but much larger inclusions of the same nature in meteoric irons etched in the same manner.

Etching for phosphide.—Boiling neutral sodium picrate is the most reliable method for identifying schreibersite and all phosphide-bearing areas. Alkaline sodium picrate may or may not color phosphide. Used boiling it usually does not color it unless long applied. Used electrolytically it is apt to do so unless the immersion is brief. Etching with a boiling neutral solution is the only perfectly dependable method if picrate is employed.

Because of its dangerous nature, neutral sodium picrate should not be prepared or used without competent instruction or advice. This caution applies especially to the preparation of the picrate in crystalline form, which is highly dangerous because the crystals are a powerful explosive which may go off easily from the effects of warmth or manipulation.

It can be prepared and used, however, with safety in the wet way without crystallizing out and drying the picrate. When the solution is to be used boiling, in the ordinary manner, it is prepared in the proportions of 2 grams of picric acid crystals and 25 grams of sodium hydroxide dissolved in water, the acid being added to the hydroxide solution.

It is not easy to determine the neutrality of the solution by the use of an indicator, as it quickly changes in color to orange, red, and brown, but litmus paper can be used satisfactorily. The solution must be neutral; for if it is acid it is ineffective, and if it is alkaline it will color carbide as well as phosphide.

The necessary length of boiling is variable, depending on the changes in the solution as well as on the character of the phosphide areas. Usually a few minutes is enough to darken all phosphide. The solution must be used immediately, as it rapidly loses its potency.

To bring out eutectic structures in phosphide inclusions the sample should be immersed in the boiling solution repeatedly for brief periods (5 to 10 seconds) as the action is often rapid, examining the sample after each immersion. In such cases the process is delicate, the structure appearing with just the right length of application and disappearing in a few more seconds in a uniform black.

Etching for carbide.—Boiling alkaline sodium picrate darkens carbide (cohenite). The solution, which must be freshly made, is prepared by dissolving 25 grams of sodium hydroxide in 100 cc. of water and adding 4 grams of picric acid. A larger quantity may be prepared in the same proportions. The use of the solution involves no danger. It must be used immediately, and care must be taken to make sure that it is at all times alkaline, as it tends to become neutral and in that case it would not darken carbide.

Though a considerable length of time is required for coloring carbide (cementite) in artificial irons, the action on cohenite is rapid. In some cases the author has found it colored after one minute in the boiling solution.

Electrolytic etching with this solution has been found by the author to be a very quick and effective method for identifying cohenite. For small samples a beaker is convenient, the cathode being the sample; the anode may conveniently be a piece of stainless steel. The current, of about 6 volts and 1½ amperes, may be obtained from three dry cells if desired.

The solution, prepared cold, becomes warm and turns rapidly to orange, red, dark red, and brown. The action on cohenite apparently is confined to the orange and red stages, with little additional effect from longer application. The action is very quick, 5 or 10 seconds being usually enough to darken cohenite inclusions. It is best to immerse the sample in the hydroxide solution before adding the picric acid. The result is not a true etch, but only a coloration from the deposition of a stain which is very easily scratched and is readily removed from the sample by a light application of rouge. Cohenite inclusions not infrequently take on brilliant prismatic colors which apparently are permanent.

The action of the electrolytic process is irregular, depending on the volume of current acting upon the surface of the specimen, which in turn depends upon its size. The results, at their best, are very perfect.

Another method, which the author has used to some extent, is the use of Murikami's reagent. It is used to identify the ternary iron-tungsten carbides in tungsten steels, which are quickly colored blue at room temperature, though cementite is not affected unless the reagent is used boiling. Cohenite is colored brown when the solution is used boiling for 5 to 10 seconds. Schreibersite is affected only slightly, if at all, if the application is brief.

The solution should be freshly prepared, in the proportions of 10 grams of potassium ferricyanide and 10 grams of potassium hydroxide in 100 cc. of water. Like sodium picrate, it is not strictly an etchant but deposits a stain.

This method has one advantage over electrolytic etching, in that its action is regular and more controllable. On the other hand, the coloration is less satisfactory and scratches appear conspicuously. Even with the finest abrasives, it was found impossible to produce a surface that would not show scratches.

Examples of all the methods described are shown in plate 63.

Electrolytic etching with chromic acid is often used to identify carbide in artificial irons, but the above methods have been found more satisfactory for distinguishing cohenite. In a few cases chromic acid was used, with negative results, to prove the absence of carbide.

Effects on fine structures.—Reference has been made elsewhere to the fact that the attack of any solvent etching reagent is stronger along the interfaces of any two components. As a result, fine structures are quickly affected by any ordinary acid etchant. Thus dense plessite and ataxites darken with even very light etching, and the same is true of kamacite when it possesses an acicular gamma-alpha transformation structure. (See Chapter XI.) For the same reason an imperfectly transformed gamma-alpha aggregate, when very fine, may appear black and unresolved even at high magnification.

It is to be noted that the action of neutral sodium picrate on phosphide, and of alkaline sodium picrate on carbide, is not a true etch but only the deposition of a colored film. Therefore there is no attack by these reagents along interfaces, and a surface even when filled with fine structures of kamacite and taenite shows no effect unless it contains phosphide or carbide.

Thus when phosphide is distributed in minute particles, their nature is not conclusively determined by etching with picral or nital, because they would appear black with any solvent etchant regardless of their nature. When etched with neutral sodium picrate, however, they appear black if phosphide; otherwise they would be invisible.

Preserving specimens.—Specimens polished and etched for metallographic study often tarnish or rust very quickly, and the only sure way to preserve them is to keep them in a desiccator as long as they are being worked upon. After they are no longer needed for immediate use, they should be preserved by lacquering.

With a light coat of lacquer specimens can still be studied quite satisfactorily under the microscope, although it should be removed for photographic work. That is quickly done with a bit of cotton wet in amyl acetate.

Microexamination.—For the study of microetched specimens a microscope with vertical illumination is used. The most satisfactory instruments are of the types made especially for metallographic work, but a vertical illuminator can readily be applied to an ordinary microscope. A yellow-green filter should be used.

The most useful amplification is 80 to 100 diameters (16 mm. objective), but 400 to 500 diameters should be available. For the latter magnification a 5.5 mm. objective is preferable to 4 mm. because of the more convenient working distance between the front lens and the object.

Higher powers are used at times in the study of artificial irons, requiring the use of immersion objectives; but the technique of their use is troublesome. For meteoric irons about 500 diameters is the practical limit, because the specimens are usually larger than the samples of artificial iron, and it is difficult to get the surface absolutely level on the microscope stage so that all parts of the field are in focus. Photography, besides other advantages, is effective at much higher magnification than is practicable in direct examination with a microscope.

An eye-piece micrometer should be provided for the measurement of octahedral bands and other features. By checking its divisions with a stage micrometer, or even a metric rule, measurements can be made easily.

Some form of ordinary illuminator should be available for examination at low power with oblique light.

Getting the surface of the specimen level on the stage is sometimes troublesome. For small specimens a convenient way is to place it, polished side down, on a level surface within a metal ring (a short section of a tube) of suitable height and diameter; place upon the specimen a lump of plasticine higher than the ring; and then press down upon the latter a glass microscope slide until it rests upon the ring. The polished surface is then parallel with the slide, to which it remains attached by the plasticine.

Photography.—While the microscope is the primary instrument for metallographic study, and is used incessantly in practice, photography is so important that it may be called indispensable for any extended research. Photographs offer several advantages; they make practical the use of high magnification; they are permanent and permit of exact and repeated comparisons; and—not the least important—their use involves no eyestrain. Photography also may be used with specimens too large to be examined on a microscope stage. A large or irregular specimen can easily be photographed because it lies on the stage of the camera with its polished surface down, all parts of it thus being in focus.

Photomicrography can hardly be carried on without special equipment, such as is used in metallographic laboratories, and this is not always available to those who wish to study meteoric irons. In such cases the microscope must be used. But where photography is available, the chief usefulness of the microscope is in making preliminary observations to ascertain the general structure of the sample and to determine what should be photographed. In practice nearly all such microscopic work is done at around 80 to 100 magnification.

Photomicrography, with the equipment designed for such work, involves much skill and a painstaking technique in exposure, developing, and printing. The subject is treated fully in textbooks on metallography. An instructive article on the subject by the late Prof. H. M. Boylston is reprinted as Appendix II of Sauveur's textbook on the metallography of iron and steel (1938).

Other methods of study.—A number of other methods of research, in addition to visual examination and photography, are at times useful. These relate mostly to the qualitative determination of various components.

Heat tinting.—This method, whereby Widmanstätten discovered the structure named for him, is sometimes used to reveal variations in the phosphorus content of artificial irons. The specimen is gently heated on a hotplate, over a Bunsen burner, or preferably floated on molten soft solder, and as the temperature rises there is selective coloration from the varying oxidation of the components. It is not practically useful with meteoric irons, as both the structure and the phosphide are revealed more satisfactorily by etching.

Sulphur printing.—Inclusions of troilite are quickly revealed by a sulphur print. A sheet of contact printing paper is soaked in 2 percent sulphuric acid and laid on a sheet of glass, and the polished specimen (preferably before etching) is pressed gently upon it for 10 or 15 seconds. The paper is then treated with hyposulphite, washed, and dried. Brown spots indicate the sulphide inclusions. This test is convenient to ascertain quickly the number and location of such inclusions, and sometimes to distinguish readily inclusions of graphite, which often are associated with troilite and which do not show on a sulphur print.

Hardness tests.—Hardness tests are rarely important but are convenient for a quick identification of schreibersite or cohenite, which sometimes might be mistaken for taenite. There is also an observable difference in hardness between troilite and daubréelite. The use of a fine needle is usually sufficient. For a more exact test a Bierbaum hardness tester is convenient, the diamond point carrying a 2-gram weight.

Quantitative nickel coloration.—To show the varying proportions of nickel in areas of taenite and plessite, the author after much difficulty developed a process of quantitative coloration by dimethylglyoxime. Briefly, the surface is coated with gelatine, immersed in very dilute nitric acid, then in an alkaline solution of dimethylglyoxime in water. The effect is to develop nickel nitrate on the surface beneath the gelatine, in quantities proportional to the nickel content at each point. The dimethylglyoxime then penetrates the gelatine and produces the characteristic red precipitate, faintly or strongly as the nickel content varies.

The technique is difficult and the results are uncertain, sometimes yielding success and again failure with apparently identical methods.

At its best, and with certain octahedrites, the result is a strikingly beautiful selective coloration when viewed under low or moderate magnification. The success of this method apparently depends upon the degree of variation between the nickel content of the taenite and that of the adjoining kamacite. If the conditions of transformation produced taenite with 25 or 30 percent nickel, it is colored strongly as compared with the nickel-poor kamacite; if the taenite contains only 15 percent nickel, there is only a slight contrast in the deposition of the red precipitate.

After tedious experimenting, by the author and later by his assistant, with many materials and manipulations, the best results were obtained with a 4 percent solution of gelatine filtered through bone black and hardened with formalin; a 1 percent solution of nitric acid in alcohol; and a saturated aqueous solution of dimethylglyoxime with a few drops of formalin, used at about 40° C.

The method cannot be recommended for any ordinary purposes of study.

Polarized light.—The usefulness of polarized light is limited by the fact that most of the components of meteoric irons are isometric in crystallization and therefore isotropic. Exceptions are troilite, which is hexagonal, and schreibersite, which is tetragonal; therefore minute inclusions of those substances should show extinctions, which might help to identify them when other methods are not satisfactory. In practice, however, the author has rarely made use of polarized light.

Spectroscopic analysis.—The spectroscope reveals extremely small percentages of component substances, and though its use generally is unnecessary it has been found by the author to be of value for the identification of cohenite. If the spectroscope reveals no phosphorus in an inclusion, it is not phosphide.

Grains or small inclusions of chromite, otherwise not easily recognized, might also be identified by the spectroscope. It has been used to reveal small percentages of the rare metals and other minor constituents; this, however, is a matter of chemistry or mineralogy, because such constituents have no effect upon the structure of meteoric irons.

X-ray analysis.—The use of X-ray diffraction analysis in metallography is a development of recent years. By revealing the position of atoms in a crystalline structure, this method has made it possible to establish the space lattice for different transformation phases, and for various metals, and to determine compositions and crystalline planes.

Even very recently some metallographers have doubted its practical value, although that now seems to have been abundantly proved both as to artificial and natural irons. More than a decade ago it was applied by Leonhardt (1927) to the study of meteoric irons, and it has been used by Heide (1932) to determine the crystallization of schreibersite and cohenite; by Borchert and Ehlers (1934) to determine the orientation of schreibersite inclusions with respect to the planes of kamacite; by Smith and Young to determine the nickel content of taenite bodies and the orientation of their planes; by Mehl and Smith (1934), Mehl, Barrett, and Jarabek (1934), and Mehl and Derge (1937) in studies of the Widmanstätten structure; and by Bradley (1939), Bradley and Goldschmidt (1939), and Owen and Sully (1939) in discussions of meteoritic structures and in support of certain suggested changes in the iron-nickel diagram.

The scope of this work has permitted no more than incidental references to the results of such investigation, but in the bibliography works are mentioned that should be useful to those who wish to pursue the subject further.

XVIII. BIBLIOGRAPHY

Systematic treatises.—The older literature on meteorites is extensive, and it is important from the standpoint of descriptive, chemical, and mineralogical treatment. There are, however, only the following systematic treatises on the subject:

EMIL WILHELM COHEN: Meteoritenkunde, 3 volumes: Volume 1, 419 pp., 1894; volume 2, 302 pp., 1903; volume 3, 419 pp., 1905, published in Stuttgart. This great work treats the entire subject in all its aspects. The third volume was intended to include full descriptions of all meteorites, but that effort was cut short by the author's death. Fortunately, however, it contains descriptions of all ataxites, hexahedrites, and fine and finest octahedrites, then known. Very full references accompany every description and chapter.

OLIVER CUMMINGS FARRINGTON: Meteorites, their structure, composition and terrestrial relations, 233 pp., 1915, Chicago. This valuable work, well illustrated, was prepared to supply the need of a treatise in English on meteorites. It summarizes much of the information contained in the works of Cohen and of other writers.

GEORGE PERKINS MERRILL: Composition and structure of meteorites. U. S. Nat. Mus. Bull. 149, 62 pp., illus., 1930. A general treatise, with many excellent illustrations. The photographs of irons are at low magnification.

STANISLAS MEUNIER: Météorites. Encyclopédie chimique, vol. 2, 532 pp., 1884. Though of minor value now, this work contains many descriptions and important observations on composition and structure in the light of the knowledge then available.

H. H. Nininger: Our stone-pelted planet, 237 pp., illus., 1933, Cambridge. A nontechnical treatment of the general subject, with illustrations and an important compilation of all then-known meteorites.

Fletcher G. Watson: Between the planets, 222 pp., illus., 1941, the Harvard books on astronomy, Philadelphia. A useful recent discussion of asteroids, comets, and meteors, with a number of chapters on meteorites.

Descriptions and studies.—Descriptions and studies of particular meteorites are mostly in the form of articles in scientific periodicals, and in the publications of scientific bodies. A large proportion of them have been reprinted separately, many of which are in the libraries of universities and museums in this country. Only a very few embody the results of metallographic study.

The following collected descriptions and studies are important:

Aristides Brezina: Die Meteoritensammlung des k. k. naturhistorischen Hofmuseums am 1 Mai, 1895. Ann. naturh. Hofmuseums, vol. 10, pp. 17–370, illus., 1895; usually cited as Wiener Sammlung. It contains, besides descriptions and illustrations, much valuable comment. An earlier edition appeared in 1885.

Aristides Brezina and Emil Wilhelm Cohen: Die Struktur und Zusammensetzung der Meteoreisen erläutert durch photographische Abbildungen geätzter Schnittflächen, 1886–1890 (no pagination). A collection of photographs of many irons, natural size or at low magnification, published between 1886 and 1890, quarto plates of mounted photographs with descriptive matter.

Emil Wilhelm Cohen: Meteoreisen Studien. A series of detailed studies of many irons, chemical and physical researches, etc., published in Annalen des k. k. naturhistorisches Hofmuseums, Vienna, and separately reprinted in 14 parts from 1892 to 1905.

Oliver Cummings Farrington: Catalogue of the meteorites of North America, to January 1, 1909. Nat. Acad. Sci. Mem. 13, 513 pp., 1915. A very important reference work, summarizing with copious references the descriptions from all sources of all meteorites of the North American Continent.

George Perkins Merrill: Handbook and descriptive catalogue of the meteorite collections in the United States National Museum. U. S. Nat. Mus. Bull. 94, 207 pp., 1916. Voluminous and profusely illustrated, with descriptions, analyses, references, and other information.

Stanislas Meunier: Revision des fers météoriques de la collection du Muséum d'Histoire Naturelle de Paris. Soc. Hist. Nat. d'Autun Bull. 6, pp 217–297, 1893. Contains much useful descriptive matter and other information.

E. A. Wülfing: Die Meteoriten in Sammlungen und ihre Literatur, 460 pp., 1897, Tübingen. A catalogue of all meteorites then known, with their distribution in collections, each with copious references.

Catalogs and lists.—In addition to the foregoing the following may be mentioned:

George T. Prior: Catalogue of meteorites with special reference to those represented in the collection of the British Museum (Natural History), 196 pp., 1923. The catalog is intended to include all known meteorites, whether represented in the museum or not, in most cases with condensed information as to history, distribution, etc. Useful for reference.

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Bibliographies; current literature.—The following are useful compilations of the literature of meteorites of later dates than Cohen's Meteoritenkunde:

H. Michel: Fortschritte in der Meteoritenkunde seit 1900. Fortschritte Min., Krist. Petr., vol. 7, pp. 245–336, 1922. Abstracts of new descriptions, new analyses, and other information.

H. Heide: Fortschritte in der Meteoritenkunde. Fortschritte Min., Krist. Petr., vol. 21, pp. 225–275, 1937. Notes of new discoveries and abstracts of descriptions.

Chemical Abstracts: This great current compilation, with cumulative indexes, includes abstracts of all published articles on meteorites in all languages. It is accessible in many libraries and is the most useful index to contemporary literature on the subject.

Popular Astronomy: The department entitled "Contributions of the Society for Research on Meteorites" contains articles, descriptions, bibliographies, lists, and other useful information, which are collected and reprinted annually under that title.

Illustrations.—Though photomicrographs of meteoric irons are becoming commoner in scientific literature, the amount of such illustrative material is still meager. The most instructive collection of such pictures, 65 in number, including meteoric irons and artificial alloys, accompanies Vogel's "Über die Strukturformen," etc. (1927), and a smaller number by the same author in "Eine umfassendere Deutung," etc. (1932). See the literature cited. The publications of Pfann (1917) and Berwerth (1918) include the earliest of such photographs.

Only a few new meteorites have been described by metallographic methods with photomicrographs. One such description by Heide and three by the author are included in the table of references.

Metallography.—Hitherto no general treatise on the metallography of meteoric iron has appeared, and information on that subject is available only in articles in scientific and technical publications, especially in those of the iron and steel trade, and in the proceedings of scientific bodies. Most of these may be found in the libraries of universities and technological institutions.

Many of the more important of such articles have been referred to in the text of this work and are listed alphabetically in the table of references.

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PLATES

The first three plates (A-C) present, for purposes of comparison, typical iron-carbon structures in artificial irons. The other plates (1–78) illustrate 97 meteoric irons, the names of which are indexed below. All specimens illustrated are from the author's collection unless otherwise indicated.

In engraving the plates the size of the photographs has been reduced by 40 percent; thus an original magnification of 100 diameters appears as 60, one of 2,000 as 1,200, etc.

All the original photographs, and many others, of the irons here illustrated are in a collection of about 1,300 photomicrographs of meteoric irons bound in five volumes, with descriptive and interpretive data on each, deposited in the United States National Museum, where they may be conveniently consulted. The negatives of all of them are also on file in the Museum, where prints from any of them may be obtained.

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ILLUSTRATIONS

PLATE A

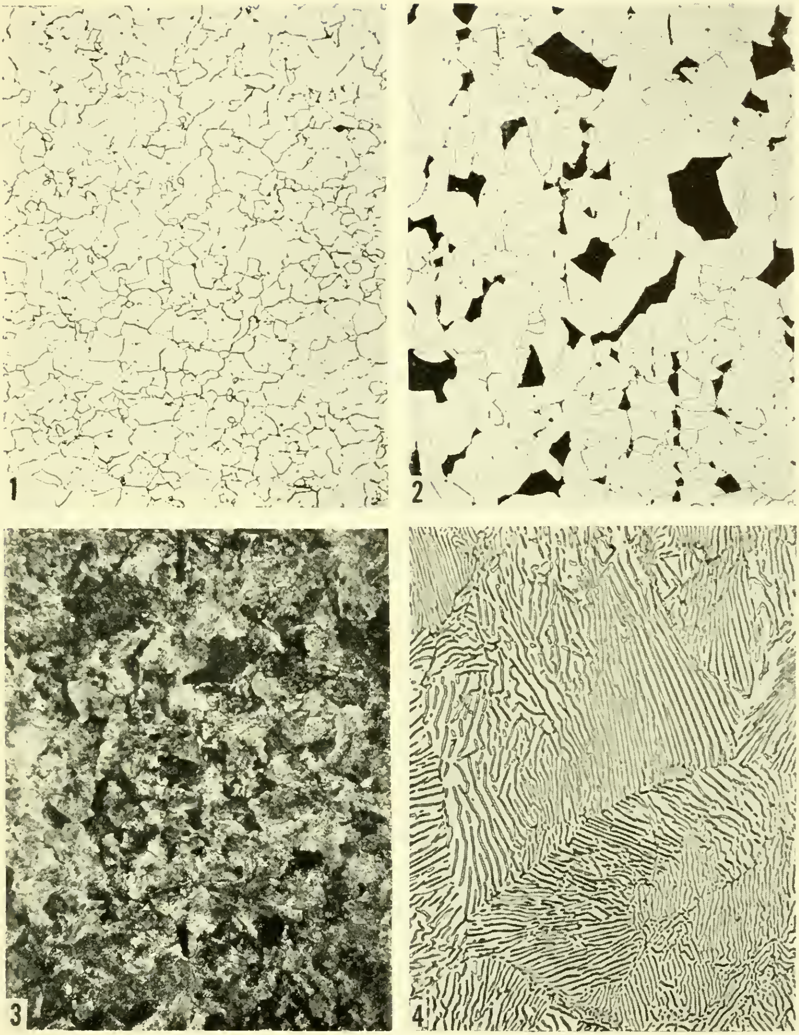
(Artificial Irons)

1. *Ferrite.* Practically pure iron, showing the characteristic microstructure of irregular polygonal grains. Strong nital etching; × 60.

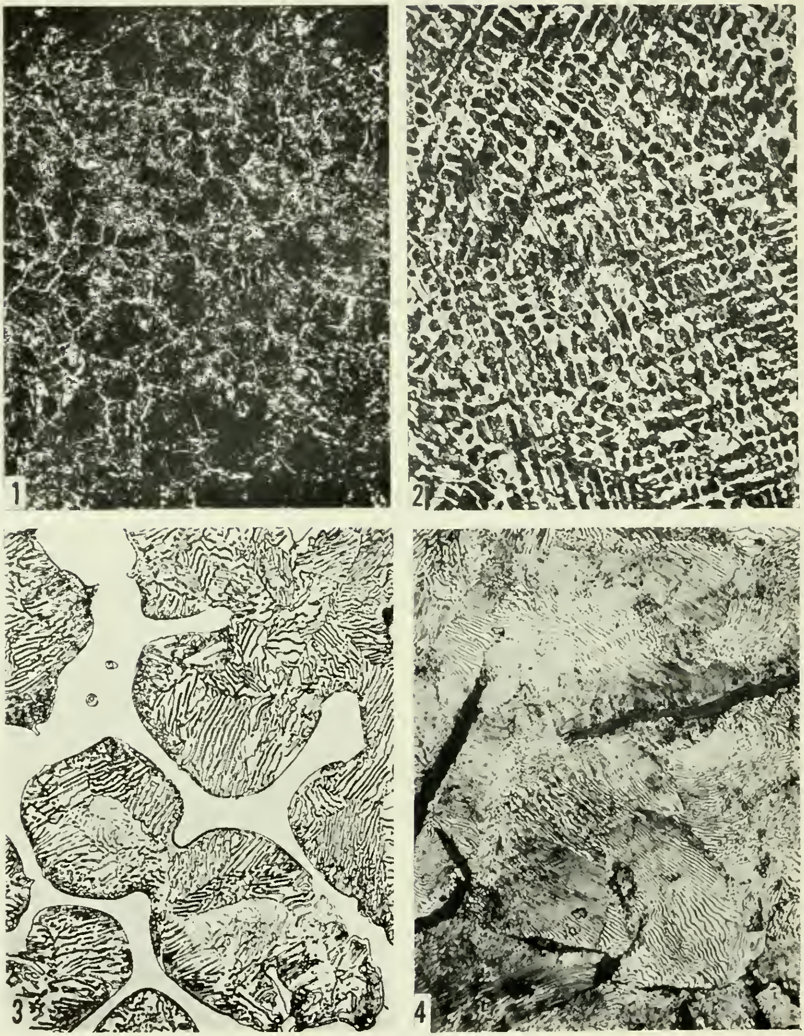
2. *Hypoeutectoid steel* (carbon 0.15 percent). It consists predominantly of ferrite. The black areas are pearlite, which when resolved at higher magnification appear as in figure 4. Strong nital etching; × 60.

3. *Eutectoid steel* (carbon 0.85 percent). It is composed entirely of the ferrite-cementite eutectoid, pearlite. Light nital etching; × 60.

4. *Pearlite* (carbon 0.85 percent). A portion of the structure shown in figure 3, consisting of lamellae of ferrite (dark) and cementite (light). Light picral etching; × 600.



Artificial Irons.



Artificial Irons.

Plate B

(Artificial Irons)

1. *Hypereutectoid steel* (carbon 1.10 percent). The carbon content being above the eutectoid ratio (0.80 percent), pearlite now predominates, with cementite segregating along grain boundaries. Compare plate A, figure 2, in which ferrite predominates. Strong nital etching; × 60.

2. *White cast iron* (carbon about 3.3 percent). The structure consists of dendrites of pearlite (black) in a matrix of cementite. Strong picral etching; × 60.

3. *White cast iron;* the same as figure 2; × 600. The pearlitic structure of the dendrites is shown.

4. *Gray cast iron* (carbon about 3 percent). Under the conditions of cooling and composition (some silicon probably being present) the carbon in excess of that necessary to form pearlite is rejected as flakes of graphite. Light nital etching; × 600.

PLATE C

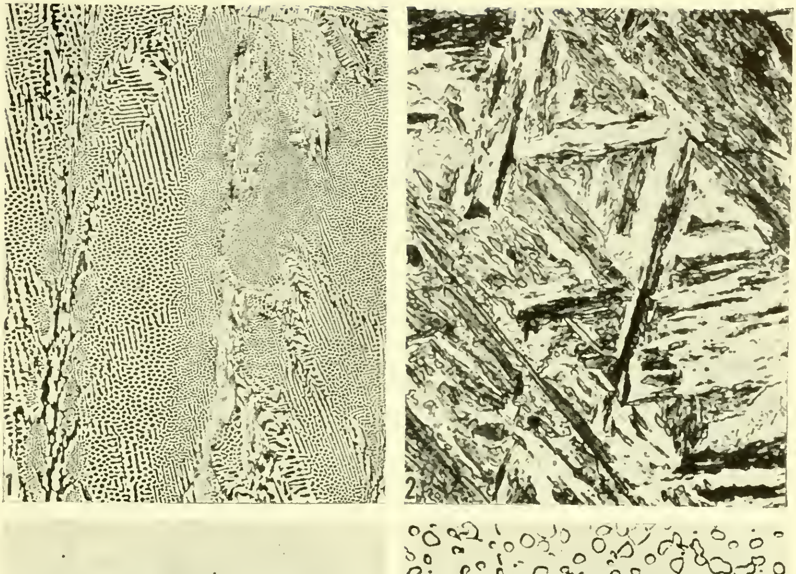
(Artificial Irons)

1. *Eutectic cast iron* (carbon 4.24 percent). The structure is a eutectic of cementite and pearlite. The groundmass (white) is cementite, Fe_3C; the black particles are pearlite and at high magnification would show a lamellar structure similar to that in plates A and B. Fairly strong nital etching; × 60.

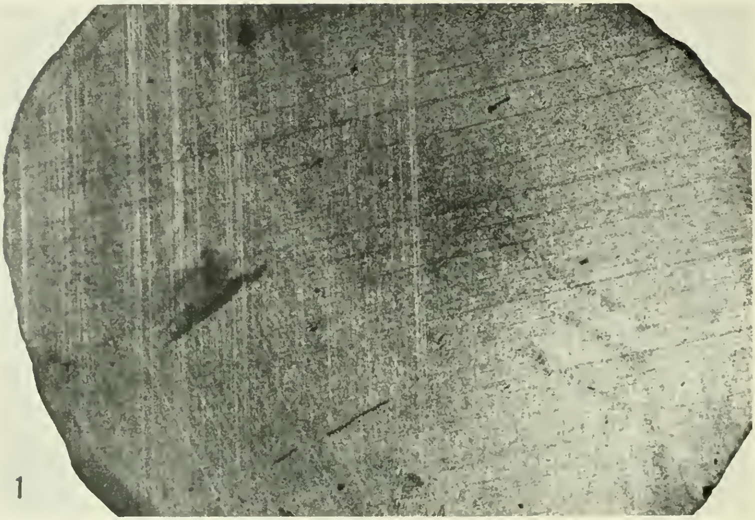
2. *Martensite.* The photograph shows the martensitic structure in a 0.55 percent steel, quenched in water from the gamma range. Fairly strong nital etching; × 600.

3. *Fine pearlite* (*troostite*) *in martensite.* The dark component, an unresolved black at lower magnification, is here shown to be not an amorphous aggregate but lamellar, essentially pearlite. Very light picral etching; × 1,200.

4. *Spheroidized cementite.* A steel of about the eutectoid composition, after prolonged annealing in the upper alpha range. The pearlitic structure has disappeared, the cementite lamellae having coalesced into spheroids. Light nital etching; × 600.



ARTIFICIAL IRONS.



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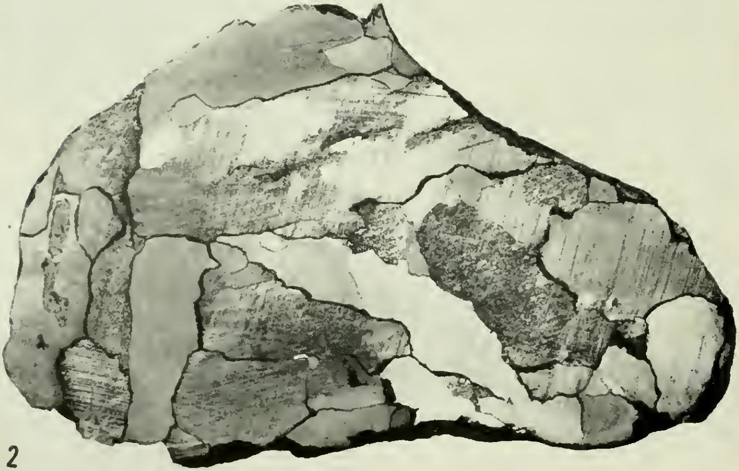


2

COAHUILA AND SANDIA MOUNTAINS METEORITES.

PLATE 1

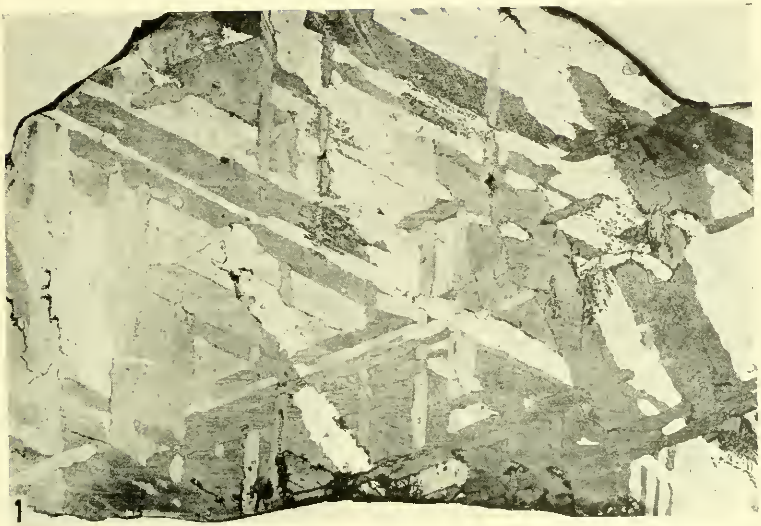
1. COAHUILA, Mexico; hexahedrite; Ni-Co 6.37 percent. A typical example of a "normal" hexahedrite, showing no structure except Neumann lines, which run without change of direction throughout the mass. This is one of the Coahuila group of irons known as Sanchez Estate. Macroetch; three-fifths natural size, ordinary light. U. S. National Museum.

2. SANDIA MOUNTAINS, New Mexico; granular hexahedrite; Ni-Co 6.45 percent (Henderson, 1939). This iron is transitional between hexahedrites and octahedrites and, like a number of similar irons, has been classed by some as a coarsest octahedrite. Inasmuch as the composition and microstructure are typical of hexahedrites, and no clear octahedral pattern is recognizable, the author would class it as a hexahedrite. Compare Santa Luzia, plate 2. Macroetch; three-fifths natural size. U. S. National Museum.

PLATE 2

1. ARISPE, Mexico; coarsest octahedrite; Ni 7.04 percent (Whitfield, in Ward, 1902). The pattern is more regular than in many coarsest octahedrites. The kamacite bands average 3 or 4 mm. wide, though some are as wide as a centimeter (e. g., in lower right of photograph. In many places two or more bands having the same oriented sheen are grouped together in a fascicle, separated by very tenuous taenite lamellae. There apparently is no plessite. Macroetch; three-fifths natural size, ordinary light.

2. SANTA LUZIA DE GOYAZ, Brazil; coarsest octahedrite; Ni-Co 6.23 percent (Meen, 1939). This, like Sandia Mountains (plate 1), is a transitional type. Though containing even slightly less nickel-cobalt than Sandia Mountains, it contains an appreciable amount of taenite, and in the upper part of the photograph an octahedral pattern is clearly discernible. The microstructure in general is typically hexahedral (plate 4). Owing to the coarseness of the structure, the analysis perhaps indicates a somewhat lower nickel-cobalt content than the actual average for the entire mass. Two large rosette inclusions of schreibersite occur in a large rounded area of kamacite. Macroetch; three-fifths natural size. U. S. National Museum.



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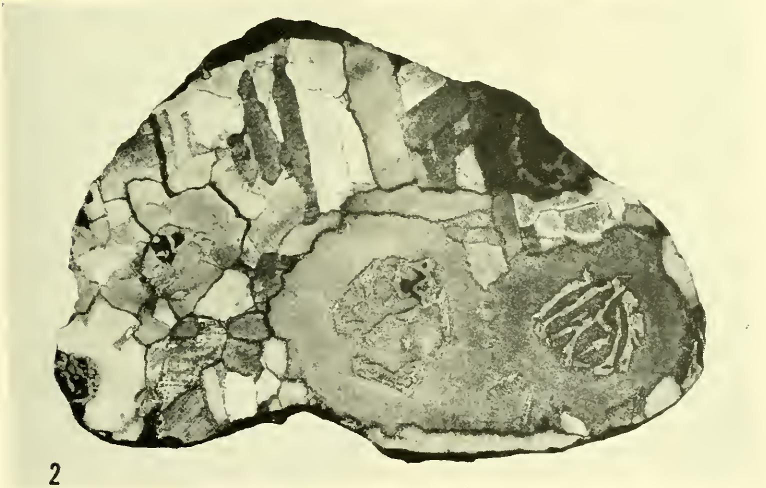
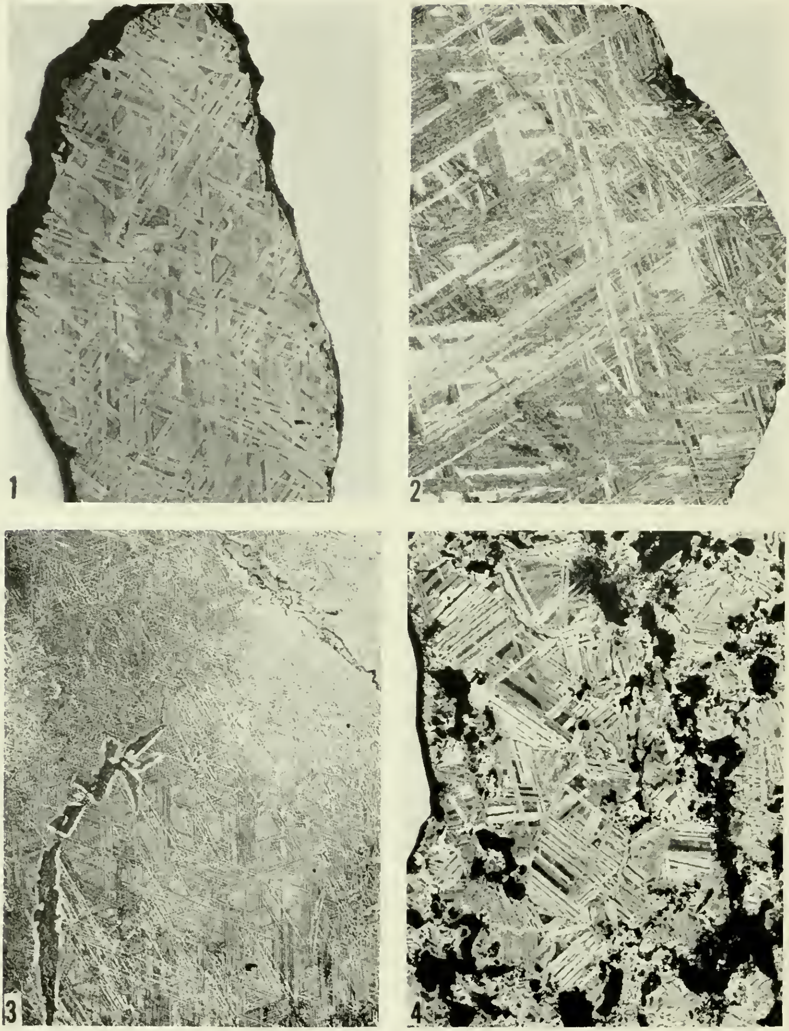


2

Arispe and Santa Luzia de Goyaz Meteorites.



STAUNTON, GRAND RAPIDS, CARLTON, AND FOUR CORNERS METEORITES.

PLATE 3

1. STAUNTON, Virginia; medium octahedrite; Ni-Co 8.16 percent (Whitfield, in Campbell and Howe, 1903). A typical medium octahedrite with a regular pattern, the kamacite bands averaging about 1 mm. in width. Macroetch; three-fifths natural size, ordinary light.

2. GRAND RAPIDS, Michigan; fine octahedrite; Ni-Co 10.69 percent. A typical fine octahedrite with a regular pattern. Brezina gives the width of the bands as 0.3 mm. Macroetch; three-fifths natural size, ordinary light. U. S. National Museum.

3. CARLTON, Texas; finest octahedrite; Ni-Co 13.40 percent. This is one of the finest of octahedrites and also one of the most regular and beautiful. Brezina gives the width of the bands as 0.2 mm., although some are narrower. A striking feature of this iron is the numerous large, irregular, elongated inclusions of schreibersite surrounded by swathing kamacite, two of which appear in the photograph. Some of these inclusions reach lengths of 12 or 15 cm. Macroetch; three-fifths natural size, ordinary light.

4. FOUR CORNERS, New Mexico. A fine granular octahedrite with silicate inclusions. The Ni-Co content of the metallic part is 10.16 percent. It shows a pattern of coarse grains, reaching dimensions of 2 or 3 cm., each with an independently oriented octahedral structure. This remarkable iron is apparently unique, though somewhat resembling Copiapo, Chile. The dark areas are silicate. Macroetch; three-fifths natural size, ordinary light.

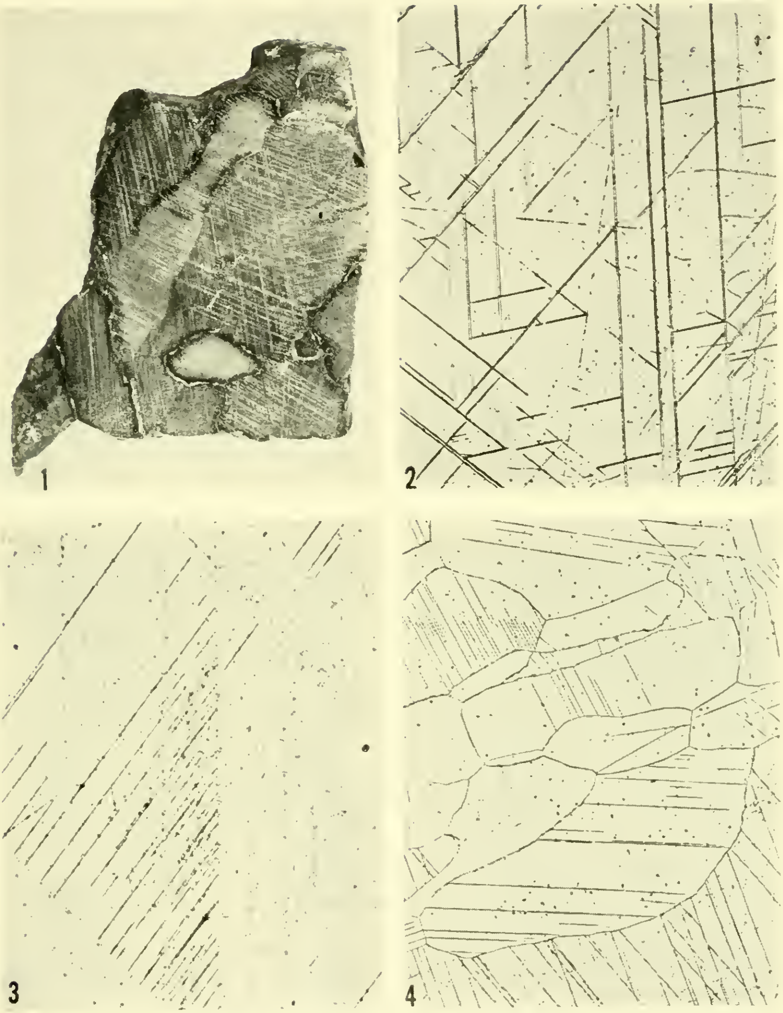
PLATE 4

1. SANTA LUZIA DE GOYAZ, Brazil; coarsest octahedrite. An example of strongly developed Neumann lines at low magnification. This iron is transitional between hexahedrites and octahedrites, and the structure here shown is duplicated in a number of irons classed as granular hexahedrites or coarsest octahedrites. Compare plates 1 and 2. Macroetch; × $1\frac{1}{2}$, ordinary light.

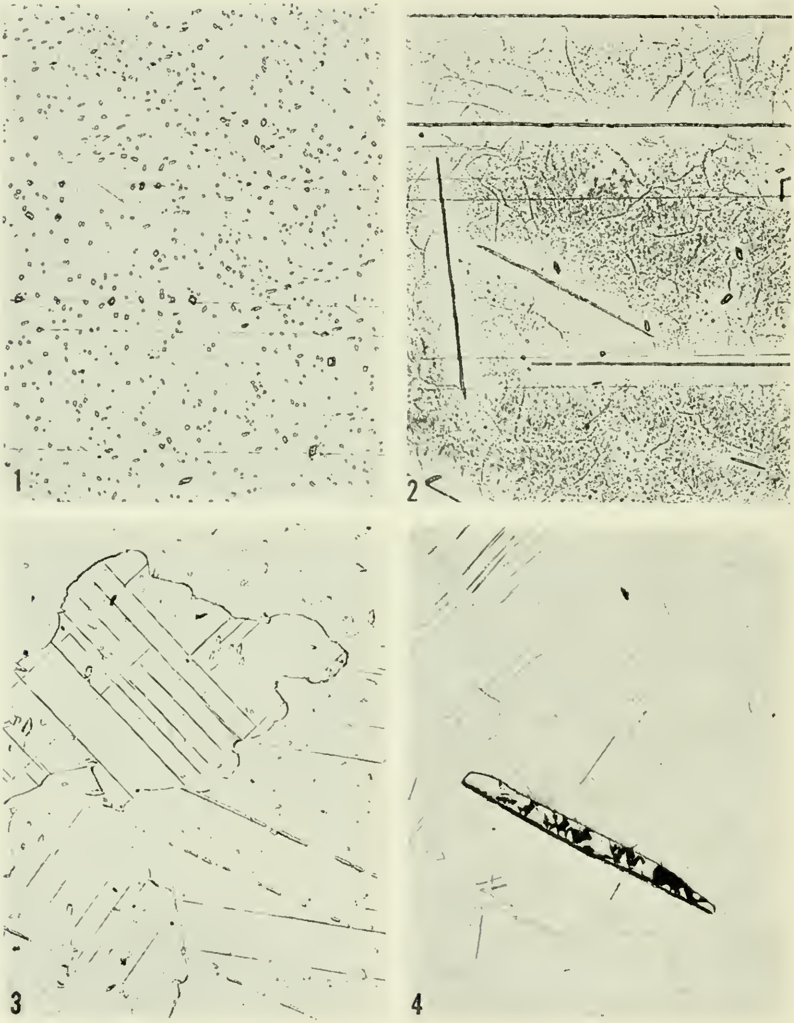
2. SCOTTSVILLE, Kentucky; hexahedrite; Ni-Co 6.28 percent, P 0.23 percent. An unusual profusion of Neumann lines. Six sets are easily distinguished, with one short line in a seventh direction (about 2 cm. long near the center of the upper half of the photograph). A little below it there is a trace of another short line parallel with it. This area is almost free from inclusions of phosphide, which in other parts of the iron are abundant. Picral; × 60. U. S. National Museum.

3. SCOTTSVILLE. Peculiar localization of Neumann lines. Four sets can be distinguished. Picral; × 60.

4. CEDARTOWN, Georgia; hexahedrite; Ni-Co 5.80 percent. Large grains with Neumann lines diversely oriented. Other parts of this iron show no grains and the lines are parallel and uninterrupted. Picral; × 90.



Santa Luzia de Goyaz, Scottsville, and Cedartown Meteorites.



Fort Duncan, Indian Valley, and Tombigbee River Meteorites.

PLATE 5

1. FORT DUNCAN, Texas; hexahedrite; Ni-Co 5.87 percent, P 0.23 percent. Typical structure of a "normal" hexahedrite, with very abundant rhabdites; two sets of Neumann lines. Picral 75 seconds; × 30.

2. FORT DUNCAN. Rhabdites give place to very long oriented schreibersite needles (lamellae) and a dispersion of minute phosphide particles. The particles, as usual in such cases, are absent in the immediate vicinity of the lamellae, the growth of the latter having absorbed the phosphide from the surrounding mass. Picral 75 seconds; × 30.

3. INDIAN VALLEY, Virginia; hexahedrite; Ni-Co 6.09 percent, P 0.27 percent. This iron, prevailingly "normal" in structure, nevertheless is marked in some places by scattered grains with a strong sheen, appearing like snowflakes. Two such grains are shown in the photograph. The directions of the Neumann lines indicate the different orientations of their planes which give rise to the variable sheen. Picral 60 seconds; × 60.

4. TOMBIGBEE RIVER (Desotoville), Alabama; hexahedrite; Ni-Co 4.78 or 5.01 percent. A finely granular hexahedrite with Neumann lines variously oriented in the grains. A needle (lamella) of schreibersite, the black marks due to surface chipping. Light picral; × 60. U. S. National Museum.

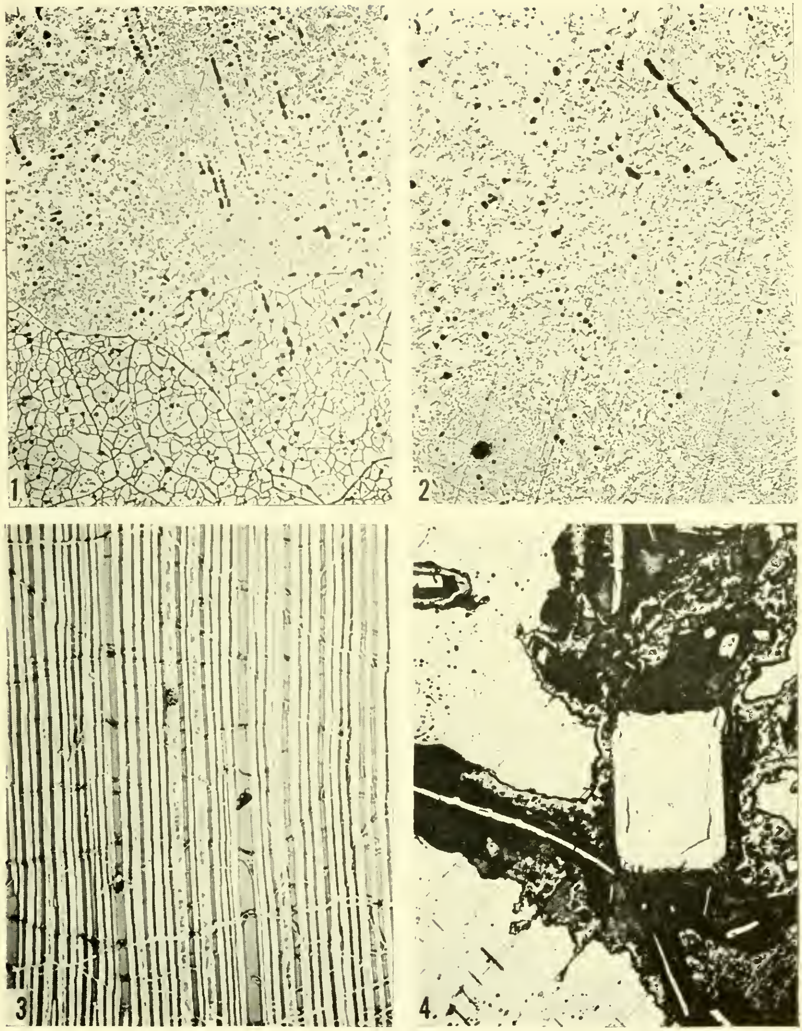
PLATE 6

1. HOLLAND'S STORE, Georgia; granular hexahedrite; Ni-Co 6.35 percent. This peculiar iron shows two distinct areas of structure. The greater part consists of macroscopic grains with diversely oriented sheen, within which is a finer granulation; the remainder resembles a nickel-poor ataxite, though occasionally enclosing small spots of granulation. The picture shows the abrupt transition from the one to the other. Picral 75 seconds; × 30.

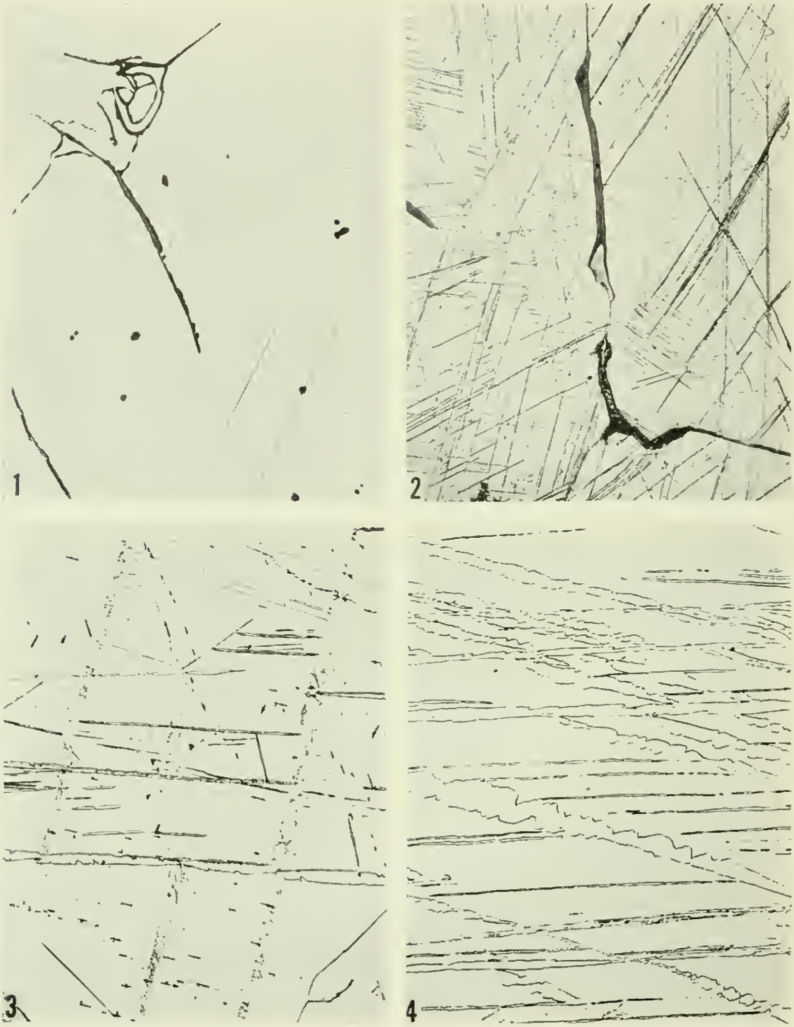
2. HOLLAND'S STORE. Part of the area without granulation. One set of Neumann lines is visible. The lines are generally absent, though in one part of the specimen several large rounded grains, bounded by thick black lamellae, show a profusion of them. The black particles, in part aligned on a hexahedral plane, are apparently oxide, though Brezina mentions the occurrence of grains of magnetite. Picral 40 seconds; × 60.

3. WALKER COUNTY, Alabama; hexahedrite; Ni-Co 5.94 percent. An anomalous pearlitic structure, the only example observed by the author in a hexahedral iron. The gray lamellae are taenite, darkened slightly with rather strong etching by reason of supersaturation with respect to kamacite, as in the pearlitic areas in San Cristobal. Compare plates 29, 30. The alternate clear lamellae are kamacite. Picral 40 seconds; × 600.

4. WALKER COUNTY. The white quadrangle, surrounded by oxide, has the pearlitic structure shown in figure 3. This minute spot was the only place where the structure was found. Picral 40 seconds; × 60.



HOLLAND'S STORE AND WALKER COUNTY METEORITES.



Pine River, Cape York, Casas Grandes, and Nelson County Meteorites.

Plate 7

1. Pine River, Wisconsin. This iron, to be described by E. P. Henderson and the writer, might be provisionally designated as an atypical coarsest octahedrite with accessory silicates. The photograph shows a sparing development of very fine Neumann lines. The irregular group of inclusions (upper left) consists of schreibersite (ring shaped) and taenite (V-shaped). The black spots are silicate; the black lines along the grain boundary are oxide. Light picral; × 60.

2. Cape York, Greenland; medium octahedrite; Ni-Co 8.47 or 8.72 percent. Part of a wide kamacite band with a profusion of Neumann lines. Irregular lamellae of taenite, darkened because of supersaturation with respect to kamacite, along the boundary of a large grain. Picral 100 seconds; × 30.

3. Casas Grandes, New Mexico; medium octahedrite; Ni-Co 8.20 percent. Fine, broad, and very broad Neumann lines. The unusual breadth in one set is due to the section's having been made at an acute angle with the twinning planes of the bands. Picral 60 seconds; × 60. U. S. National Museum.

4. Nelson County, Kentucky; coarsest octahedrite; Ni-Co 7.12 percent (Henderson, in Henderson and Perry, 1943). Very broad Neumann lines similar to those in figure 3, at higher magnification. The microstructure of this iron is generally hexahedral, although on large surfaces wide octahedral bands are apparent. Picral 60 seconds; × 150.

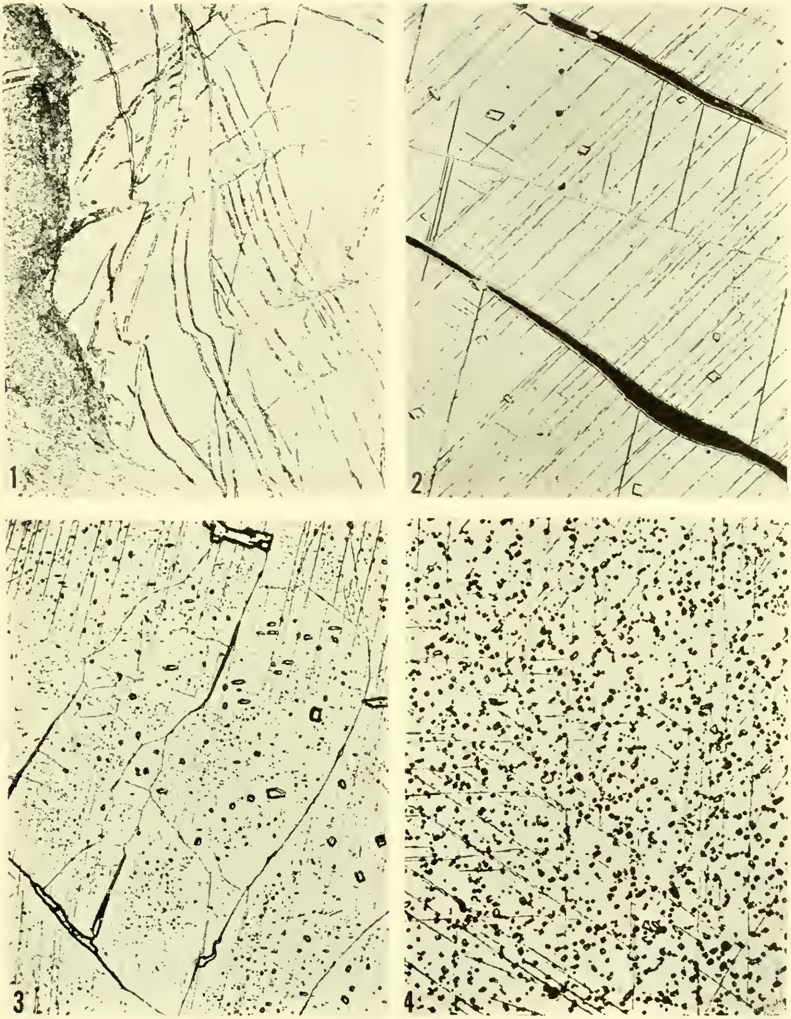
PLATE 8

1. HENBURY, Australia; medium octahedrite; Ni-Co 7.48–7.91 percent. Irregular Neumann lines. The specimen is a small flakelike mass that has suffered severe distortion; in larger masses the structure of Henbury is regular. Picral 45 seconds; × 60.

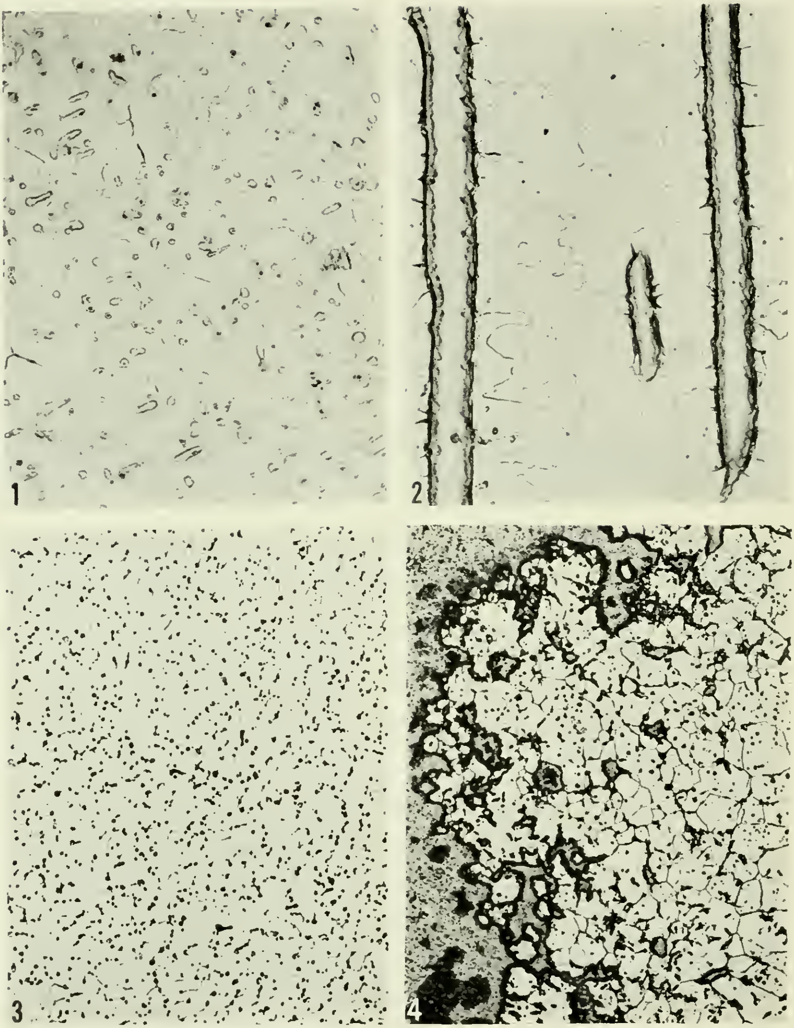
2. SEELÄSGEN, Prussia; coarsest octahedrite; Ni-Co 5.74 percent. Broad kamacite bands between taenite lamellae. One set of Neumann lines crosses them without change of direction. Three other sets may be distinguished. Picral 60 seconds; × 60.

3. BENDEGO, Brazil; coarse octahedrite; Ni 6.8 percent. Large kamacite grains with Neumann lines crossing the grain boundaries (outlines of earlier gamma grains) without interruption, as in many hexahedrites. Schreibersite bodies along grain boundaries and many rhabdites. Picral 80 seconds; × 30. U. S. National Museum.

4. FORSYTH COUNTY, North Carolina; nickel-poor ataxite; Ni-Co 6.08 percent, P 0.23 percent. Four sets of Neumann lines making angles of 45° and 90°. This is believed to be the first observed example of Neumann lines in an iron of this class. The photograph shows the general structure of the iron, kamacite with a profusion of rhabdites more or less altered by reheating. The occurrence of Neumann lines is local. Picral 45 seconds; × 45.



HENBURY, SEELÄSGEN, BENDEGO, AND FORSYTH COUNTY METEORITES.



Chesterville and Forsyth County Meteorites.

PLATE 9

1. CHESTERVILLE, South Carolina; nickel-poor ataxite; Ni-Co 6.55 percent. General structure, showing rhabdites and phosphide particles, deformed and partly diffused by heating. Fine irregular secondary granulation. Light picral; × 60. U. S. National Museum.

2. CHESTERVILLE. Schreibersite needles partly diffused, with iron-phosphide eutectic cores and thornlike projections where liquefied phosphide penetrated the surrounding iron along grain boundaries. It resembles the structure in the zone of alteration in Río Loa. Light picral; × 60.

3. FORSYTH COUNTY, North Carolina; nickel-poor ataxite; Ni-Co 6.08 percent. General structure, a profuse dispersion of minute shapeless phosphide particles in indistinctly granulated kamacite. The particles are attacked even with very light etching (3 seconds) and are quickly obliterated, leaving black spots. Picral 45 seconds; × 45.

4. FORSYTH COUNTY. Area adjacent to a large troilite inclusion, the penetration of the sulphide along grain boundaries making them much more distinct than in the iron as a whole. The ragged edge of the inclusion, and extensive penetration of the sulphide into the iron, indicate a much longer and higher heating than the atmospheric heating that produces zones of alteration. Picral 45 seconds; × 45.

PLATE 10

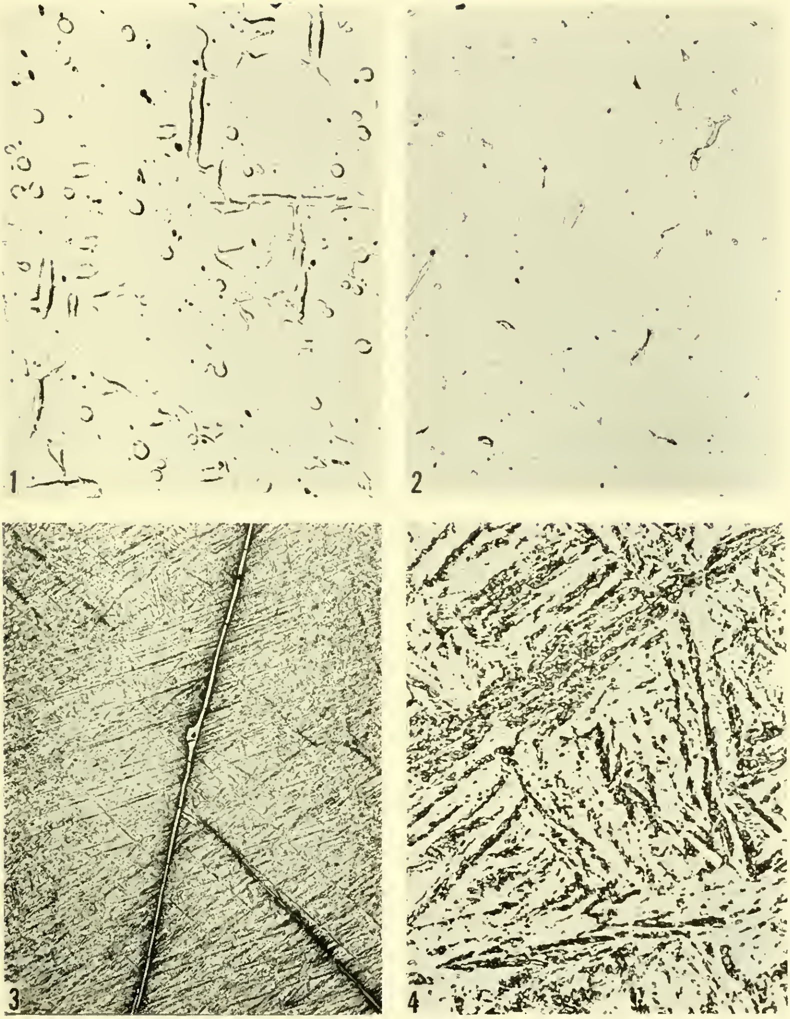
1. CINCINNATI, Ohio; nickel-poor ataxite; Ni-Co 6.11 percent, P 0.05 percent. Typical structure. Rhabdites and schreibersite needles are rounded and diffused by heating. In places the alteration is less complete, rhabdites being regular in shape with little diffusion. Picral 40 seconds; × 150. American Museum of Natural History.

The very low percentage of phosphorus shown in the analysis (Sjöström, 1898) seems inconsistent with the abundance of phosphide, not only as shown in the photograph but also in needles and numerous inclusions of phosphide eutectic (pl. 59).

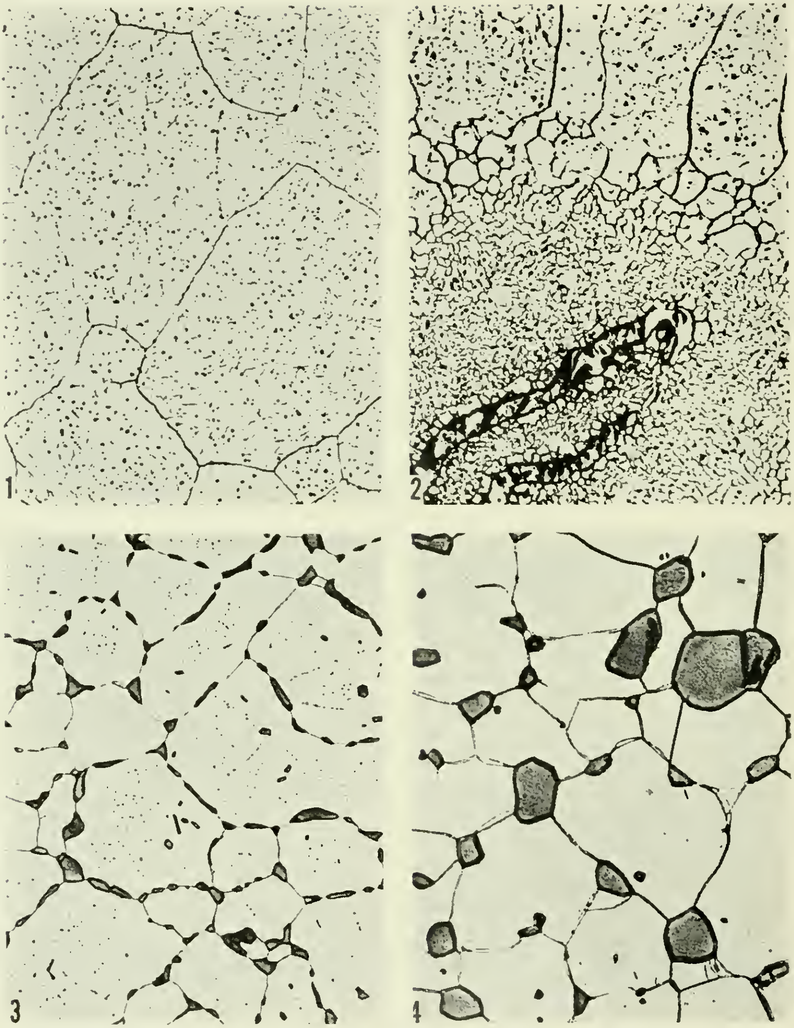
2. LOCUST GROVE, Georgia; nickel-poor ataxite; Ni-Co 6.21 percent. General structure, showing effects of heating upon rhabdites and upon larger undetermined inclusions, which probably are $Fe-Fe_3P$ eutectic. A unique structure in this iron is shown in plates 65 and 66. Picral 30 seconds; × 60.

3. PRIMITIVA (La Primitiva), Chile; nickel-poor ataxite; Ni-Co 5.43 percent, P 0.18 percent, C 0.03 percent. General structure, with a lamella of schreibersite. Though with so low a Ni-Co content this iron might be assumed to be wholly in the alpha phase, nevertheless it shows a transformation structure of gamma-alpha needles in kamacite similar to that found in many octahedrites (e. g., Trenton, Canton, Thunda, pl. 35). Though exceptional in irons so low in nickel, analogous structures were found in New Baltimore (Ni-Co 6.74), plate 77, and San Francisco del Mezquital (Ni-Co 6.33 percent; pl. 78).

4. PRIMITIVA. The general structure at high magnification. The nature of the gamma-alpha needles is clearer. Picral 20 seconds; × 600.



CINCINNATI, LOCUST GROVE, AND PRIMITIVA METEORITES.



Mejillones and Soper Meteorites.

Plate 11

1. Mejillones, Chile; nickel-poor ataxite; Ni-Co 6.26 percent, P 0.32 percent. This iron is an aggregate of macrograins, averaging about a millimeter in size, with diversely oriented sheen giving with ordinary etching an appearance of glistening flakes. The outlines of the large gamma grains have been preserved by impurities along the boundaries. The iron is filled with minute phosphide particles whose peculiar shapes indicate heat alteration. Picral 95 seconds; × 45.

2. Mejillones. In the vicinity of the schreibersite inclusion the large grains give place to finer and finer granulation, a condition found about such inclusions in other irons. In artificial irons phosphorus inhibits grain growth. Picral 95 seconds; × 45.

3. Soper, Oklahoma; nickel-poor ataxite; Ni-Co 6.91 percent, P 2.23 percent. This unusual iron, with an extraordinary proportion of phosphorus, has a structure of large grains with copious precipitation of schreibersite along the boundaries. Some minute particles of phosphide are found within the grains; otherwise the kamacite is clear and structureless. The phosphide obviously segregated in the gamma phase, contemporaneously with, or after, the formation of the grains. The structure is the same with picral etching, except that the phosphide areas are clear. Light picral and neutral sodium picrate; × 60.

4. Soper, nickel-poor ataxite. An area similar to the preceding. The phosphide bodies are shown to have a mottled structure similar to those in Helt Township (plate 55), probably indicating an iron-phosphide eutectic. Light picral and neutral sodium picrate; × 150.

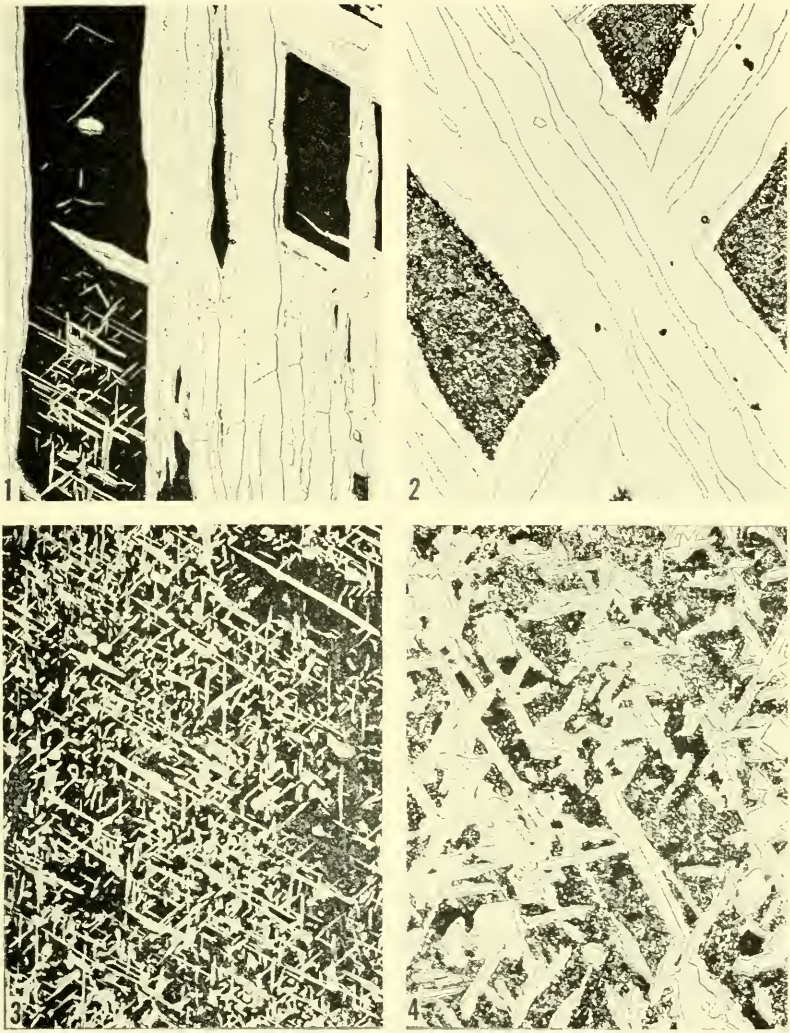
Plate 12

1. **Butler**, Missouri; finest octahedrite; Ni-Co 10.28 percent. A very regular Widmanstätten structure, the taenite approaching the kamacite in area, and all plessite fine to dense. The field at left shows kamacite needles (lamellae) octahedrally oriented. Picral 35 seconds; × 30.

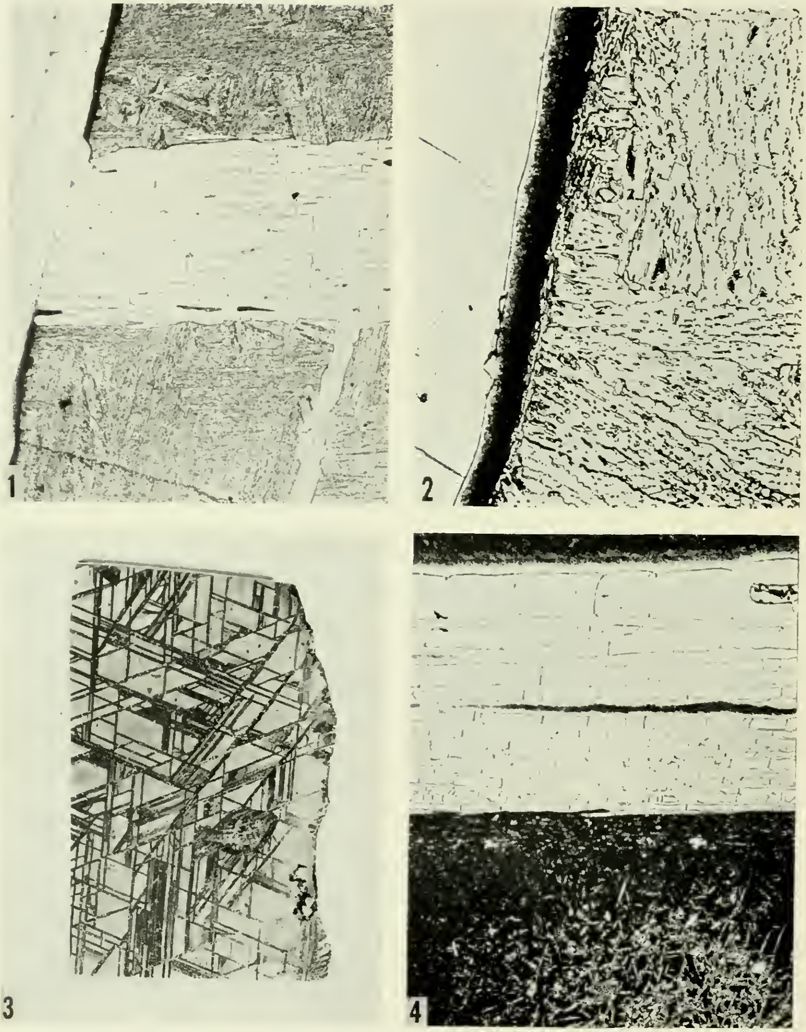
2. **Butler.** With light etching the plessite shows a structure of white alpha (kamacite) particles in a black gamma-alpha mixture of extreme fineness. Picral 10 seconds; × 150.

3. **Butler.** One of the occasional plessite fields that are filled with a profusion of kamacite particles and needles octahedrally oriented. Picral 35 seconds; × 30.

4. **Butler.** Part of the area shown in figure 3 at higher magnification. The kamacite bodies are surrounded by clear taenite. The ground mass of the iron in part consists largely of kamacite particles; in places it is a black unresolved gamma-alpha aggregate. The structure resembles that of some nickel-rich ataxites. Picral 10 seconds; × 150.



Butler Meteorite.



Grand Rapids and Carlton Meteorites.

Plate 13

1. **Grand Rapids**, Michigan; fine octahedrite; Ni-Co 10.69 percent. Though containing more nickel than Butler, the bands are not so fine. The general structure is similar to that of Carlton (below), with large fields containing oriented taenite lamellae and dark plessite. Taenite lamellae are less profuse than in Carlton because of the lower nickel content. The area shown is typical, the dark plessite being indistinctly oriented. Picral 75 seconds; × 30.

2. **Grand Rapids.** Part of the dark plessite shown in figure 1. Higher magnification shows it to be composed of minute droplike taenite bodies. Picral 40 seconds; × 150.

3. **Carlton**, Texas; finest octahedrite; Ni-Co 13.40 percent. A sample microetched; × $1\frac{1}{5}$, ordinary light. The structure is seen to consist of very narrow kamacite bands separated, for the most part widely, by plessite fields. The area of plessite largely predominates. With ordinary light the bands appear dark and the fields light. Compare plate 3.

4. **Carlton.** A kamacite band and part of a plessite field, the band containing a profusion of taenite lamellae. One lamella is an example of the so-called "spotted" taenite. The plessite is more dense than in Grand Rapids, being unresolved at moderate magnification. Below is an area of kamacite needles and spindles, such as appear in the interior of dense plessite fields in other finest octahedrites. Compare Butler, Laurens County, and Cowra, plates 12, 15, 17. Picral 75 seconds; × 30.

PLATE 14

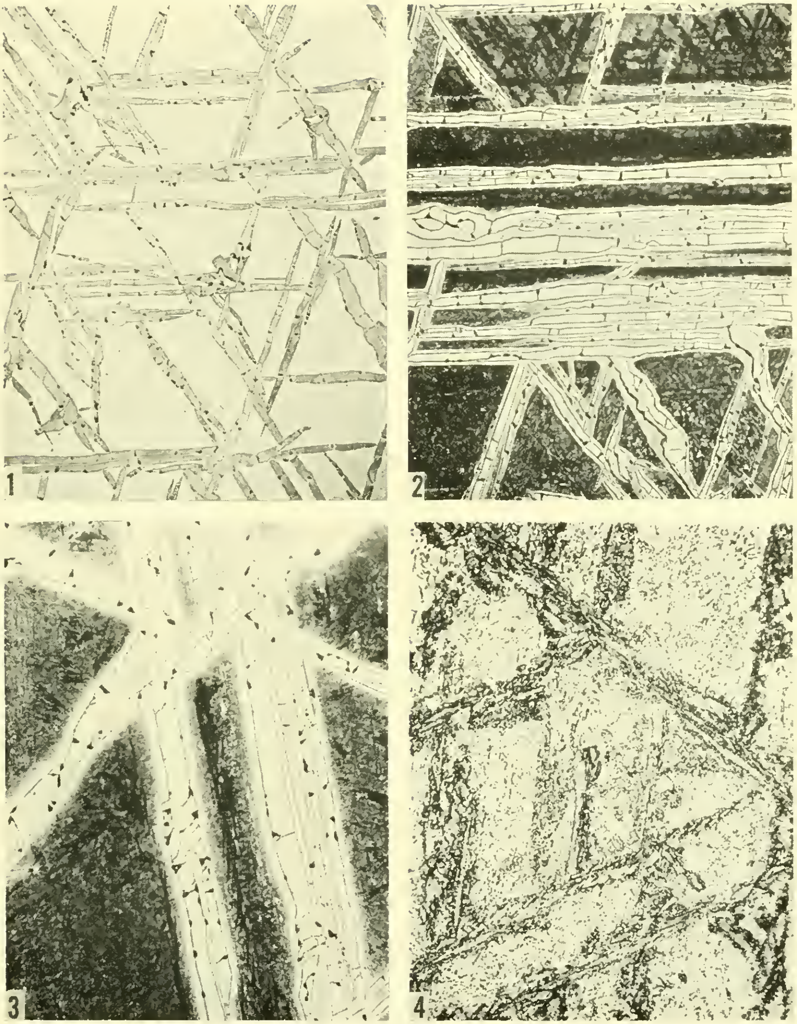
1. TAZEWELL, Tennessee; finest octahedrite. An old analysis (1855) gives Ni-Co 15.28 percent, but this is almost certainly too high, as no other iron with even 14 percent shows a typical octahedral structure. Apparently the Ni-Co content should be less than that of Cowra (pls. 17, 54).

The photograph shows the general pattern at moderate magnification and very light etching, which reveals only the kamacite bands. The graying of the bands is probably due to cold working, the dragging of the abrasive having produced a thin film of worked metal, which is dissolved away by stronger etching; see figure 2. The same effect may be seen in San Cristobal (pls. 29, 30). Picral 5 seconds; × 30.

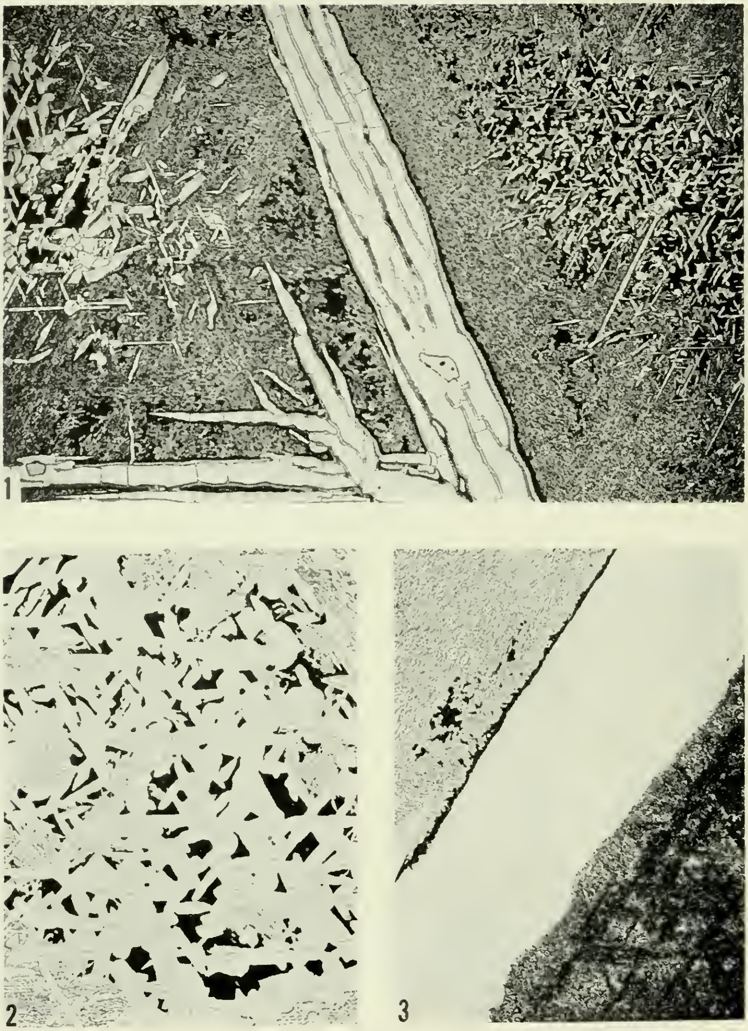
2. TAZEWELL. An area similar to the preceding, strongly etched. The kamacite bands have now become clear. The very abundant taenite lamellae, now visible, are slightly gray because their transformation could not be fully completed by reason of the rigidity of the mass at the low transformation temperature. All plessite is fine to dense. In the uppermost fields the unresolved black needles of the gamma-alpha mixture in a lighter ground are oriented. Picral 75 seconds; × 30.

3. TAZEWELL. At higher magnification the graying of taenite and the acicular pattern in plessite fields are more apparent. Picral 20 seconds; × 60.

4. TAZEWELL. Plessite with oriented acicular structure. The black needles are partly resolved. The black gamma-alpha mixture is also finely disseminated in the lighter ground. Picral 20 seconds; × 300.



TAZEWELL METEORITE.



Laurens County Meteorite.

PLATE 15

1. LAURENS COUNTY, South Carolina; finest octahedrite; Ni-Co 14.21 percent, P 0.16 percent. It may be doubted whether any iron properly classified as an octahedrite has a higher Ni-Co content than Laurens County and Cowra (14.25 percent). Though in Laurens County (unlike Cowra) the octahedral structure is clear, the plessitic groundmass more closely resembles that of ataxites. The photograph shows the general structure of very fine kamacite bands, widely spaced in plessite, which mostly shows a uniform paraeutectoid structure like that adjacent to the kamacite bands in the picture. In the centers of many plessite fields are areas of oriented kamacite needles, of which two are shown. The plessite within such areas is very dense (black), the small segregations of kamacite having left a groundmass of higher nickel content, which therefore remained untransformed to a lower temperature at which atomic mobility was so slight that the minute gamma-alpha particles remained discrete. With strong etching the taenite lamellae show gray because of supersaturation with respect to the alpha phase. Picral 60 seconds; × 30. U. S. National Museum.

2. LAURENS COUNTY. Part of a fine area of kamacite needles, similar to that in the left portion of figure 1. Some interstices are filled with light paraeutectoid plessite; the dense black areas are unresolved. Picral 25 seconds; × 60.

3. LAURENS COUNTY. Kamacite band with (upper left) lighter plessite; and (lower right) denser plessite octahedrally oriented. The abundance of taenite in this iron is reflected in the lamellae within the band and the wide taenite border along the interfaces. Small areas of dense black plessite. Picral 25 seconds; × 60.

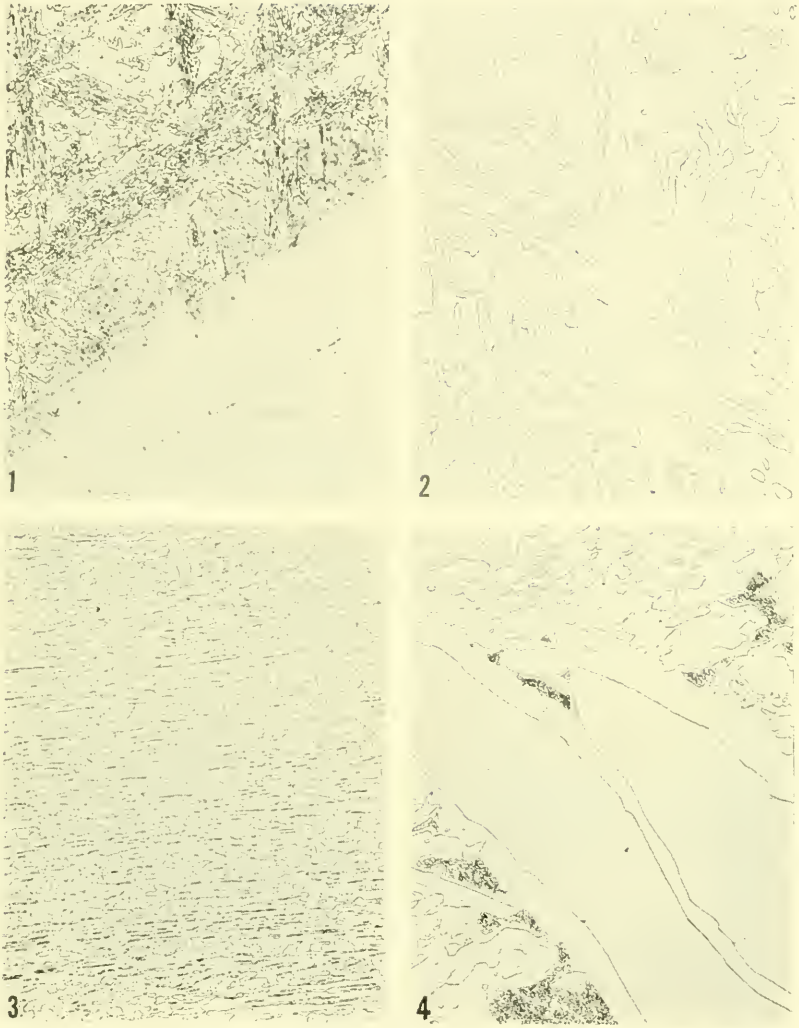
Plate 16

1. Laurens County, South Carolina, finest octahedrite; Ni-Co 14.21 percent. Part of the oriented plessite area in plate 15, figure 4. The structure is one of taenite particles, in kamacite, the former often darkened because of supersaturation, with areas of clear kamacite. Picral 15 seconds; × 300. U. S. National Museum.

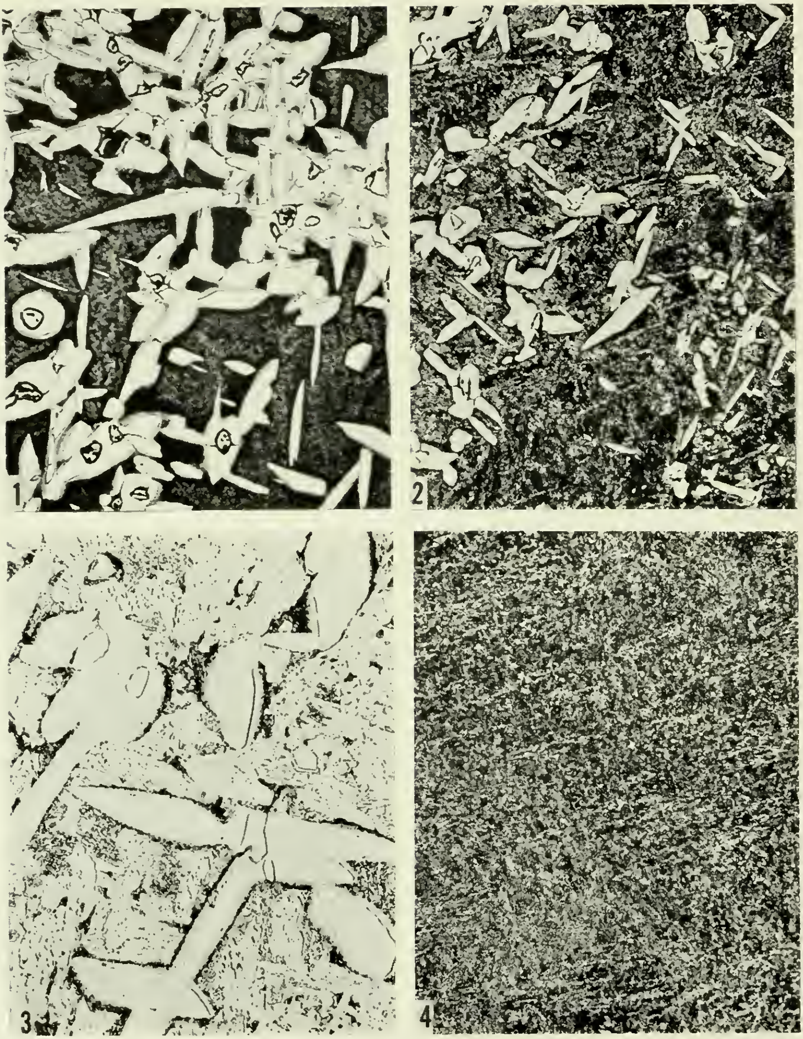
2. Laurens County. Plessite with paraeutectoid structure, taenite particles in a ground of kamacite. The structure apparently formed at a temperature at which diffusion was sufficiently active to permit a very perfect segregation of the two phases. The taenite shows no darkening, indicating no supersaturation. Picral 15 seconds; × 300.

3. Laurens County. Paraeutectoid plessite, which, perhaps because of higher nickel content, transformed at a lower temperature than that in figure 2. With a lower diffusion rate segregation was impeded, resulting in a finer structure. The particles show strong orientation. This type of plessite is more common than the former in Laurens County. Picral 15 seconds; × 300.

4. Laurens County. Two kamacite spindles in paraeutectoid plessite, with taenite borders, which merge with the taenite of the surrounding structure. In this photograph it is easy to trace the two components of the groundmass, which is often difficult in such structures. Some slightly darkened areas merge with the clear taenite bordering the spindles. The taenite in the border is clear because the excess of the alpha phase (kamacite) was completely absorbed into the kamacite spindle; farther away some of the alpha phase remained, leaving the taenite slightly supersaturated. At the tip of the upper spindle the kamacite composing it extends as if by a narrow channel, widening into the clear groundmass in which small taenite bodies appear as islands. Picral 15 seconds; × 300.



Laurens County Meteorite.



COWRA METEORITE.

Plate 17

1. Cowra, Australia; ataxite (or finest octahedrite); Ni-Co 14.25 percent. This iron, hitherto classed as an octahedrite, is transitional between octahedrites and ataxites, and more strongly resembles the latter class. It has no octahedral characteristics, except in places a trace of octahedral orientation in the kamacite needles and spindles. Such orientation in several ataxites is more distinct—e. g., Illinois Gulch, Iquique, Shingle Springs, San Cristobal (pls. 21, 22, 25, 29). General structure at moderate magnification, a thick irregular dispersion of kamacite bodies in a dense groundmass. Many of them contain droplike inclusions of phosphide-iron eutectic, as in numerous other ataxites. Picral 50 seconds; × 30. U. S. National Museum.

2. Cowra. An area where the spindles are smaller and less numerous. Picral 45 seconds; × 60.

3. Cowra. Part of the area shown in figure 2 at higher magnification. The groundmass has a confused structure, resembling that in Monahans (pl. 18). Taenite borders around the kamacite spindles are partly lacking. Picral 20 seconds; × 300.

4. Cowra. Uniform dense plessite. Such areas are found around the larger kamacite bodies; farther away small spindles like those shown in figure 2 begin to appear, and still farther the regular structure shown in figure 1. Compare Wiley and Shingle Springs, plate 51. Picral 45 seconds; × 60.

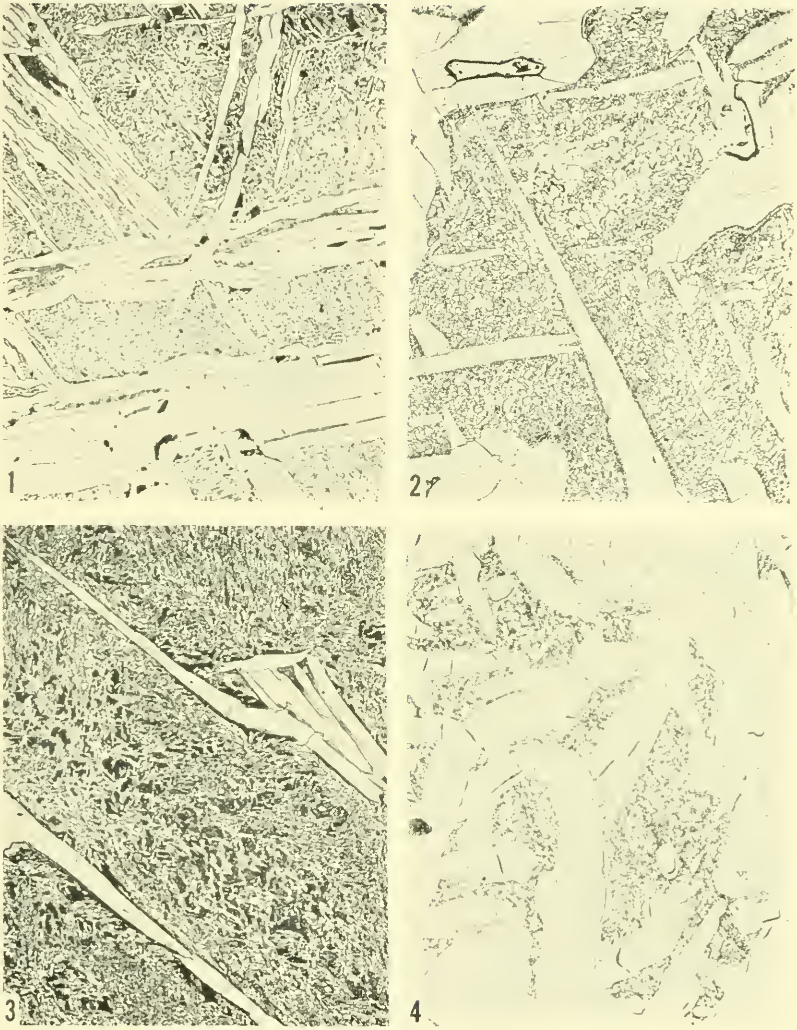
Plate 18

1. Bacubirito, Mexico; finest octahedrite; Ni-Co 10.38 percent. Though clearly an octahedrite, and with a markedly lower nickel content than some other typical finest octahedrites, this iron is close to the borderline between octahedrites and ataxites. In some areas the structure is much more irregular and confused than is here shown, in other places more regular. Picral 60 seconds; × 30.

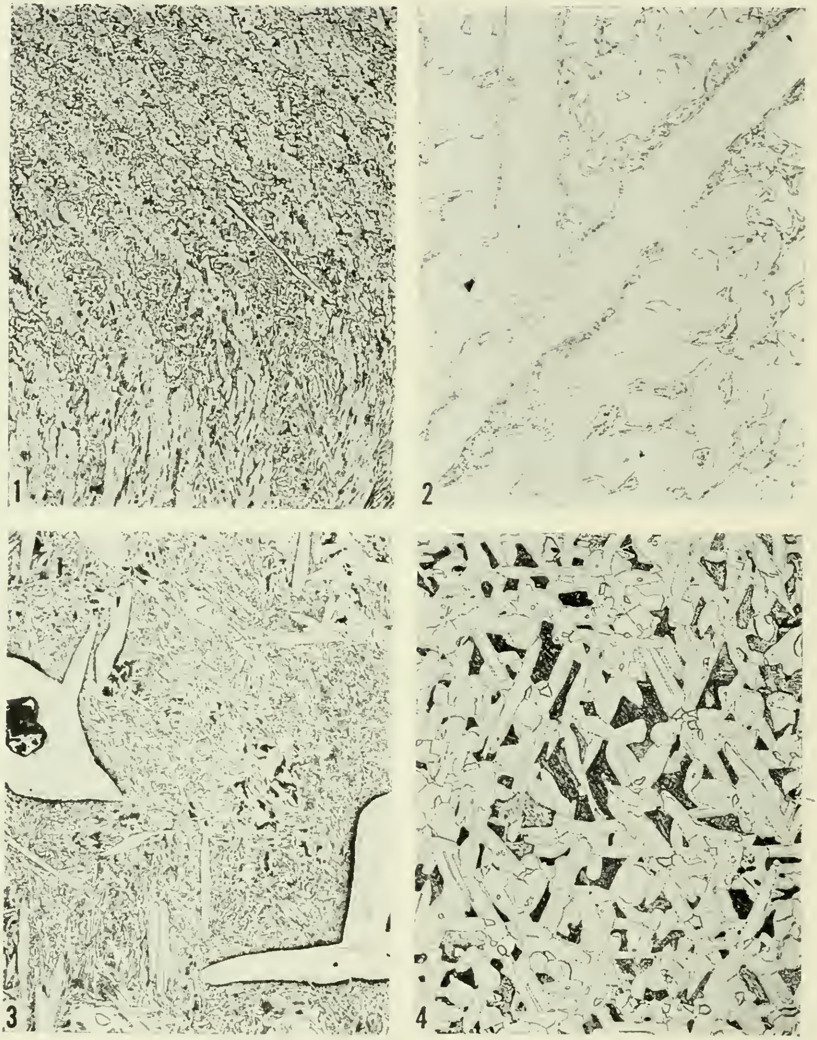
2. Ballinoo, Australia; finest octahedrite (or ataxite); Ni-Co 10.47 percent. Though described as a finest octahedrite, this iron possesses only a vestigial octahedral structure and may be regarded as transitional. Compare Monahans, below; also Wiley (pl. 19). Picral 40 seconds; × 60.

3. Monahans, Texas; nickel-rich ataxite; Ni-Co 11.51 percent. This iron is transitional between finest octahedrites and ataxites. The taenite lamellae in the photograph show vestigial octahedral orientation. The general structure of the iron, which in many places has no taenite lamellae, consists of minute kamacite bodies in dense plessite or in taenite. Picral 60 seconds; × 60.

4. Monahans. Part of the groundmass shown in figure 1. Plessitic areas show an imperfectly transformed gamma structure. In other places, they are clear, composed of homogeneous taenite. Practically the same structures are found in Bacubirito, Ballinoo, and Cowra. Picral 20 seconds; × 300.



BACUBIRITO, BALLINOO, AND MONAHANS METEORITES.



GUFFEY AND WILEY METEORITES.

Plate 19

1. Guffey, Colorado; nickel-rich ataxite; Ni-Co 11.09 percent. The nickel content of Guffey is less than that of a number of finest octahedrites, and little more than that of Bacubirito and Ballinoo. Its structure, however, resembles that of the higher-nickel ataxites, though coarser. The photograph shows the prevailing structure at moderate magnification. Picral 45 seconds; × 60. American Museum of Natural History.

2. Guffey. General structure at higher magnification. The white areas are kamacite. Taenite is darkened because of supersaturation with respect to kamacite. Picral 25 seconds; × 600.

3. Wiley, Colorado; nickel-rich ataxite; Ni-Co 12.31 percent. This iron is in the transitional class, but the author would assign it to ataxites. The kamacite body at left contains an inclusion of iron-phosphide eutectic. Picral 40 seconds; × 60.

4. Wiley. An example of the occasional areas of densely crowded kamacite spindles, the interstices filled with fine to dense plessite. Picral 40 seconds; × 60.

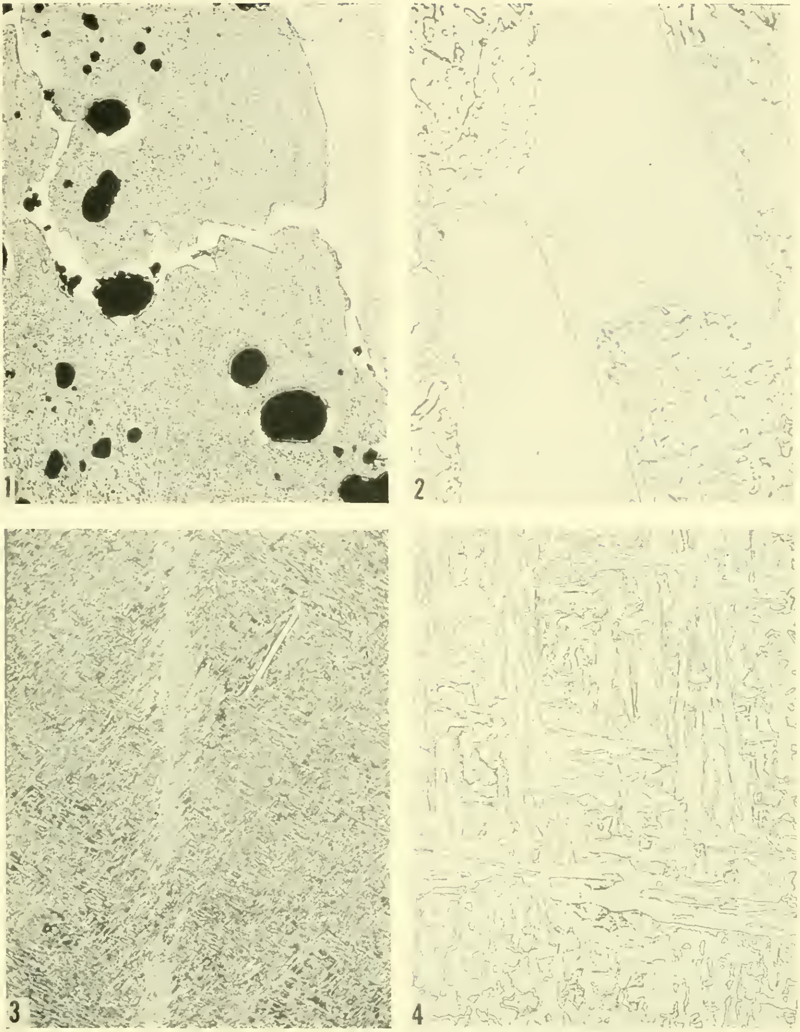
PLATE 20

1. TUCSON, Arizona; nickel-rich ataxite; Ni-Co 10.19 percent. For this class of ataxites the nickel content of Tucson is low. The photograph shows the general structure of the plessitic groundmass with irregular kamacite bodies. The black, rounded areas are forsterite, a silicate that is abundantly disseminated through the mass and that is reported to have been found in no other meteoric iron. This is from the mass of Tucson known as the Ainsa iron. Picral; × 60.

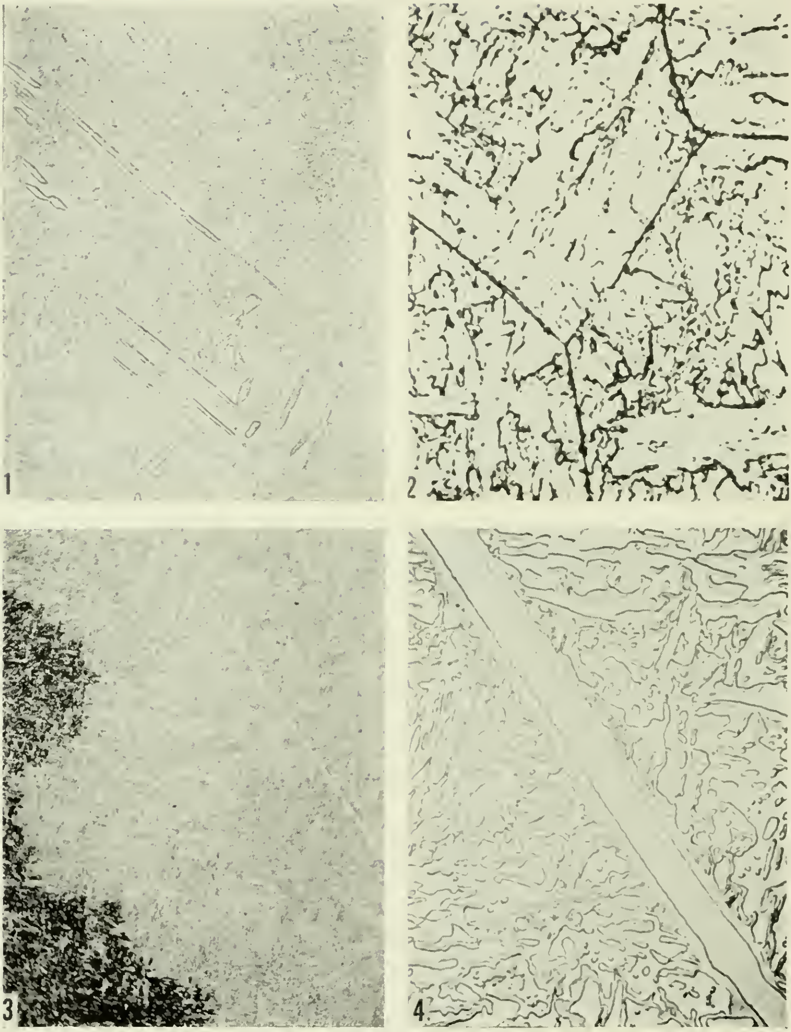
2. TUCSON. Groundmass with parts of two kamacite spindles. The groundmass shows an imperfect paraeutectoid structure of taenite particles in kamacite. The large kamacite areas are surrounded by taenite borders, but not completely; at the upper left the kamacite of the spindle merges with the corresponding component of the groundmass. The taenite border also merges in places with irregular taenite particles in the groundmass. Some of the particles are darkened because of supersaturation, but their sharp dark outlines are due to the strong attack of the etchant along their interfaces. Picral 15 seconds; × 600.

3. NORDHEIM, Texas; nickel-rich ataxite; Ni-Co 12.20 percent. General structure of the iron, a uniform gamma-alpha paraeutectoid. The nickel content is higher than in the preceding irons and the ataxite structure is more fully developed. A needle of schreibersite. Picral 50 seconds; × 60.

4. NORDHEIM. Part of the area shown in figure 3 at higher magnification. The taenite particles are slightly supersaturated, evidenced by a slight graying with fairly strong etching. Orientation is evident. Picral 30 seconds; × 300.



TUCSON AND NORDHEIM METEORITES.



Illinois Gulch and Deep Springs Meteorites.

PLATE 21

1. ILLINOIS GULCH, Montana; nickel-rich ataxite; Ni-Co 13.48 percent. General structure at moderate magnification, a paraeutectoid ground with oriented needles and spindles of kamacite. In many places such inclusions are absent. Picral etching was ineffective with this iron, bringing out no structure, as is the case with high-nickel artificial alloys. The etching was done with nitric-acetic acid, which is used on high-nickel steels to develop grain structure. In some places this iron shows faint gamma-grain boundaries at low magnification. Nitric-acetic acid 10 seconds; × 60.

2. ILLINOIS GULCH. Part of area shown in figure 1, same etching, × 600. The very irregular gamma-alpha structure reflects imperfect transformation. The outlines of gamma grains appear strongly.

3. DEEP SPRINGS, North Carolina; nickel-rich ataxite; Ni-Co 14.14 percent. Typical structure, a fine, somewhat oriented, groundmass with an occasional needle (lamella) of kamacite. The dark area at the left is due to invasion of hydroxide. The iron darkens quickly in etching. Light picral; × 60.

4. DEEP SPRINGS. Part of the area shown in figure 3. A paraeutectoid gamma-alpha structure, the phases in about equal proportions. The graying of the taenite indicates slight supersaturation. The kamacite needle (lamella) is bordered by clear taenite, growing gray at the outer edges, then merging with the taenite of the groundmass. Light picral; × 600.

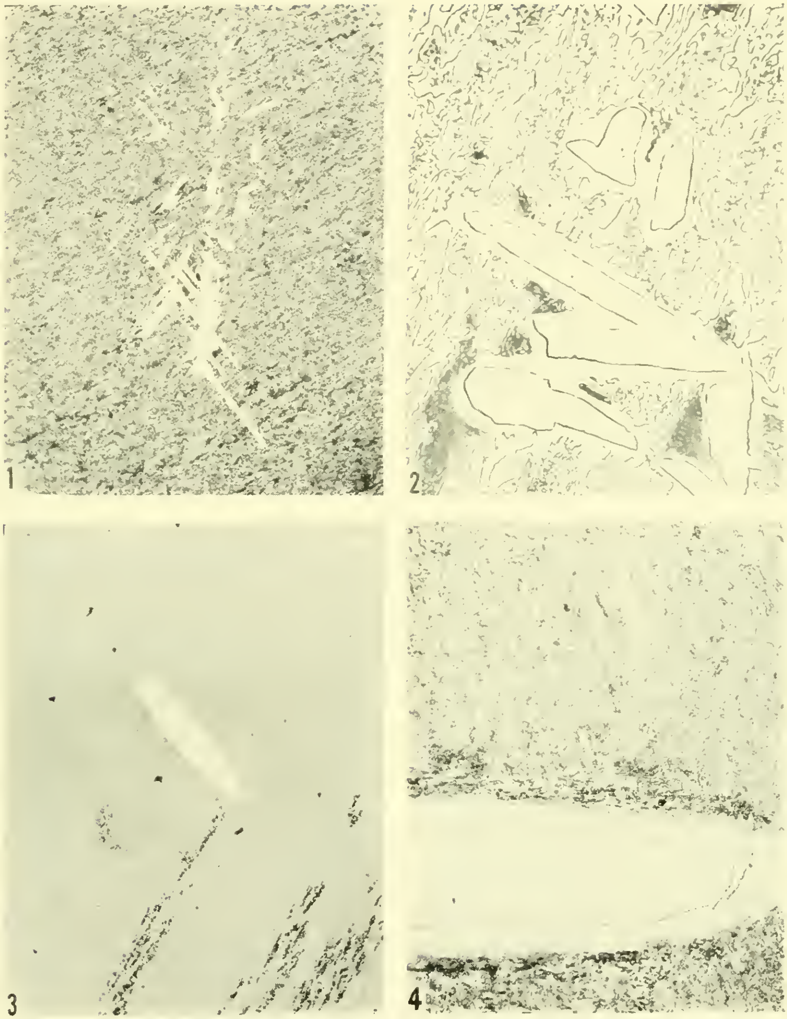
PLATE 22

1. IQUIQUE, Chile; nickel-rich ataxite; Ni-Co 16.35 percent. Typical structure of the iron, a fine groundmass with occasional oriented needles or groups of short, rounded spindles of kamacite. The iron etches slowly. Picral 70 seconds; × 60.

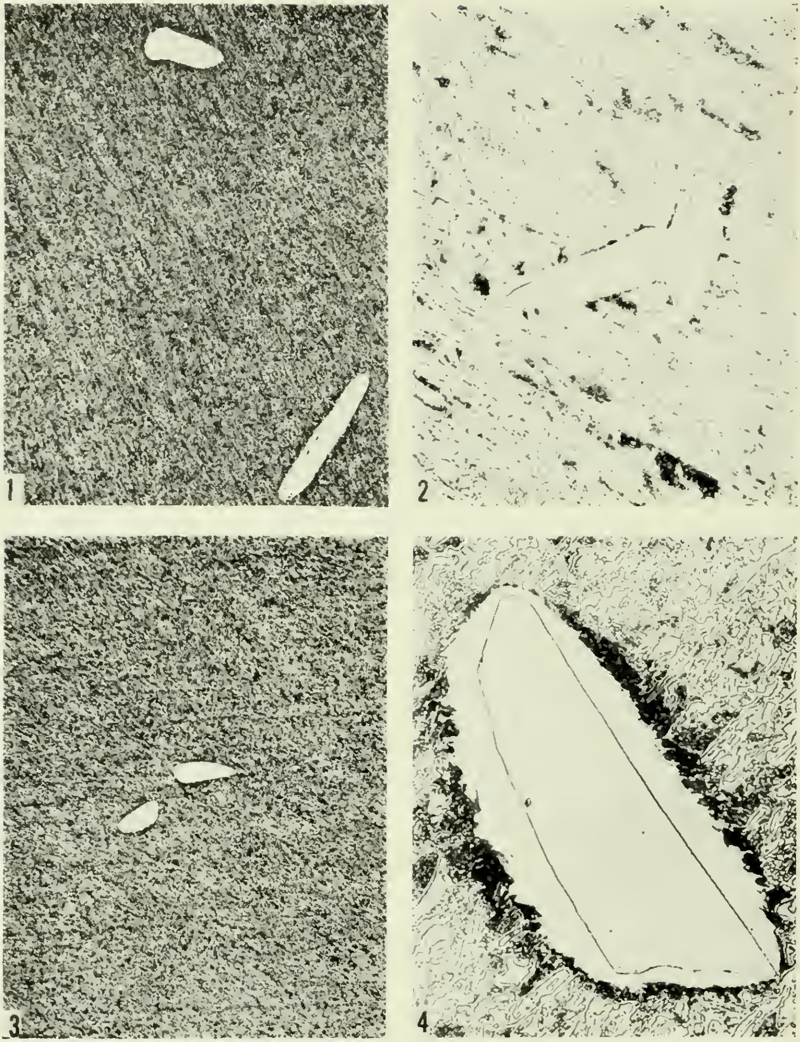
2. IQUIQUE. Part of an area similar to figure 1 at high magnification. The taenite borders of the spindles merge with the taenite of the groundmass. In places it is hard to distinguish between particles of kamacite and of taenite, both sometimes appearing clear. Where one component is darkened, however, it is always taenite, the kamacite invariably being clear. Where the two are very minutely divided in some places a uniform black results because of the strong attack of the etchant along their interfaces. Picral 70 seconds; × 600.

3. CAPE OF GOOD HOPE, Africa; nickel-rich ataxite; Ni-Co 16.62 percent. General structure, a very fine gamma-alpha groundmass with occasional needles or spindles of kamacite. The black component is hydroxide. The iron etches very quickly, turning dark and all structure disappearing. Very light picral; × 60.

4. CAPE OF GOOD HOPE. Part of the area shown in figure 3, slightly stronger etching. Dense, irregular paraeutectoid groundmass, with a minute kamacite needle in addition to the large one. The latter surrounded by a clear taenite border. Additional etching for 10 minutes with neutral sodium picrate produced no effect, showing absence of phosphide. Picral 15 seconds; × 300.



Iquique and Cape of Good Hope Meteorites.



KOKOMO AND TLACOTEPEC METEORITES.

PLATE 23

1. KOKOMO, Indiana; nickel-rich ataxite; Ni-Co 16.83 percent. General structure, with two of the occasional minute kamacite bodies. Picral 45 seconds; × 60. American Museum of Natural History.

2. KOKOMO. An area similar to figure 1. The paraeutectoid structure is irregular. The taenite border of the kamacite body merges in places with the corresponding component of the groundmass. In places the taenite shows complete equilibrium; in others a grayness indicates supersaturation with respect to kamacite. Picral 25 seconds; × 600.

3. TLACOTEPEC, Mexico; nickel-rich ataxite; Ni-Co 16.91 percent. General structure, with two kamacite spindles. Picral 50 seconds; × 60.

4. TLACOTEPEC. An area similar to figure 3 at high magnification. The kamacite spindle is seen to be surrounded by an irregular border of taenite, all in a groundmass of paraeutectoid structure in which some of the taenite particles are darkened by reason of supersaturation. In a few places the clear taenite of the border can be seen to merge with the same component of the paraeutectoid, but generally the merger is obscured by the irregular border of black gamma-alpha mixture that surrounds the spindle. Picral 25 seconds; × 600.

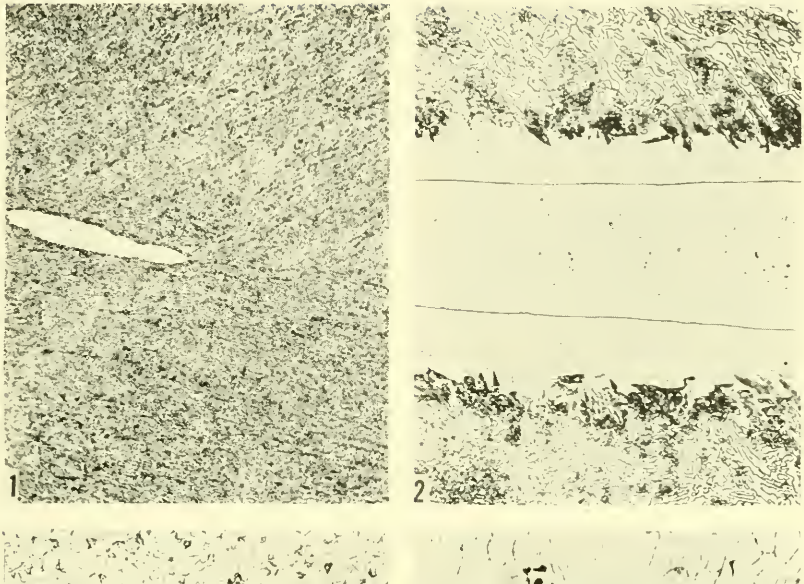
Plate 24

1. Hoba, South Africa; nickel-rich ataxite; Ni-Co 17.00 percent. General structure, with a kamacite needle. Picral 45 seconds; × 100. American Museum of Natural History.

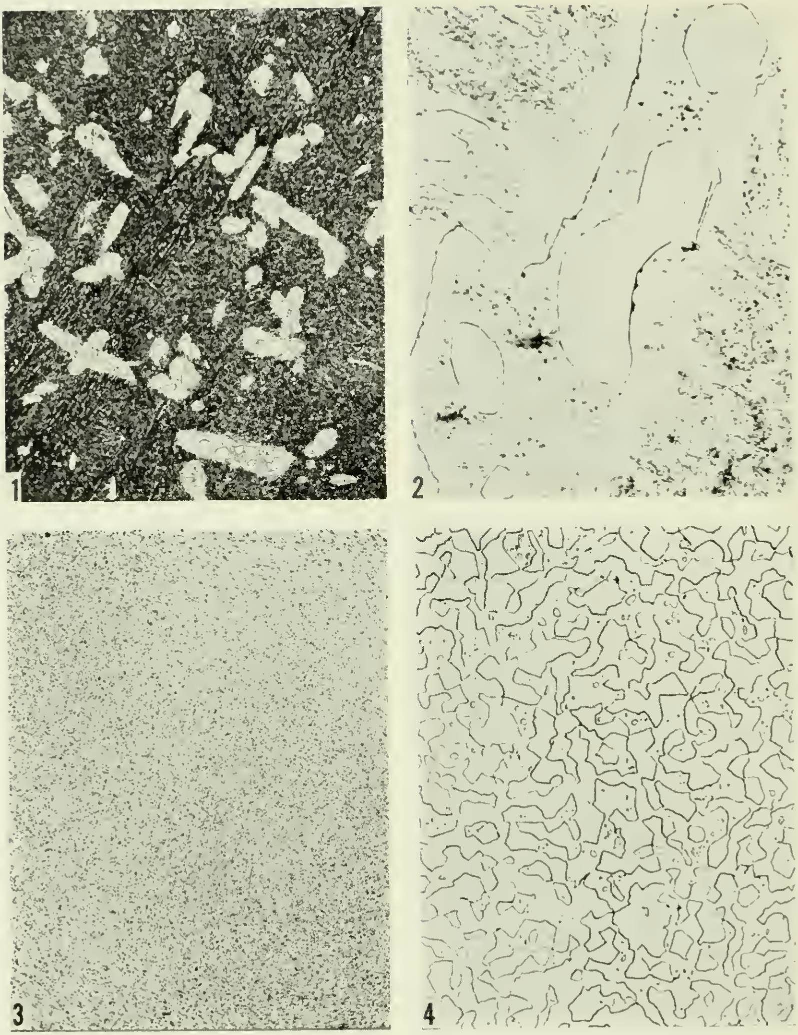
2. Hoba. Part of a kamacite needle similar to that in figure 1, with portions of the paraeutectoid groundmass. The structure quite exactly resembles that of Tlacotepec and Cape of Good Hope, but the merger of the taenite in the border with the groundmass is more evident. Picral 25 seconds; × 600.

3. Linville, North Carolina; nickel-rich ataxite; Ni-Co 17.08 percent. General structure, a very uniform and well-developed paraeutectoid structure of rounded kamacite particles in a taenite groundmass. With fairly strong etching the taenite is gray because of slight supersaturation. Many kamacite bodies contain droplike inclusions of an iron-phosphide eutectic; such inclusions show no structure with picrate etching but blacken completely. Exceptionally there are small spots where the kamacite bodies are larger and elongated, with some orientation. Picral 50 seconds; × 30. U. S. National Museum.

4. Linville. The same structure as figure 3 at higher magnification. Picral 35 seconds; × 150.



Hoba and Linville Meteorites.



Shingle Springs and Ternera Meteorites.

PLATE 25

1. SHINGLE SPRINGS, California; nickel-rich ataxite; Ni-Co 17.34 percent, P 0.34 percent. General structure of the iron, a dense groundmass with copious irregular inclusions of kamacite, somewhat oriented, of which practically all have inclusions of iron-phosphide eutectic. Strong etching (to bring out the structure of the inclusions) blackens the groundmass. Picral 50 seconds; × 60. U. S. National Museum.

2. SHINGLE SPRINGS. One of the kamacite inclusions at high magnification. The clear rounded areas are phosphide, surrounded by kamacite, which darkens with etching because of gamma-alpha admixture. The kamacite inclusion has an irregular border of clear, fully coalesced taenite which darkens as it merges with the taenite of the groundmass. The latter presents a dense and confused structure, indicative of imperfect transformation. Sodium picrate darkens the phosphide, but has no appreciable effect on the groundmass, though the phosphorus content of the iron is fairly high. Picral 20 seconds; × 600.

3. TERNERA (Sierra de la Ternera), Chile; nickel-rich ataxite; Ni-Co 17.85 percent. General structure of the iron at moderate magnification. Picral 40 seconds; × 60. U. S. National Museum.

4. TERNERA. The same structure shown in figure 3 at high magnification. The para-eutectoid is strongly and very uniformly developed, the taenite areas indicating by their clearness complete transformation. They can be distinguished from the kamacite by their minute rounded inclusions of kamacite. Picral 15 seconds; × 600.

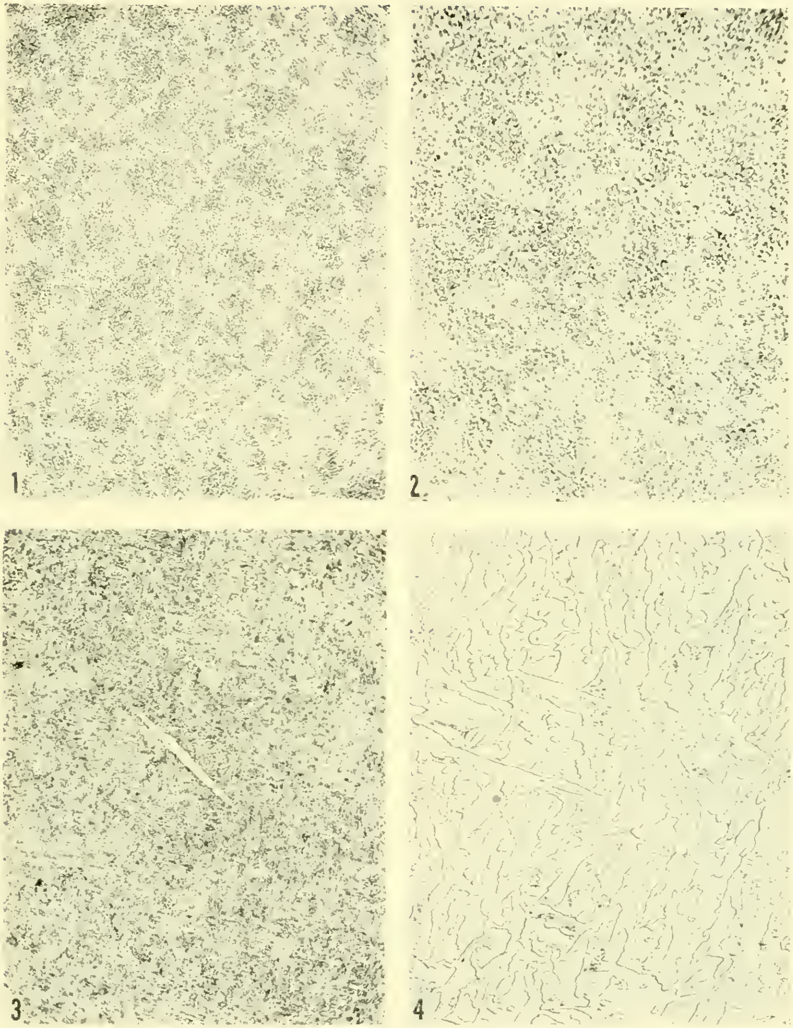
PLATE 26

1. SMITHLAND, Kentucky; nickel-rich ataxite; Ni-Co 17.36 percent. Typical structure, a fine segregation of very minute alpha (kamacite) crystallites in a gamma matrix. A phantom pattern of former large gamma grains whose boundaries have disappeared. Picral 80 seconds; × 60. U. S. National Museum.

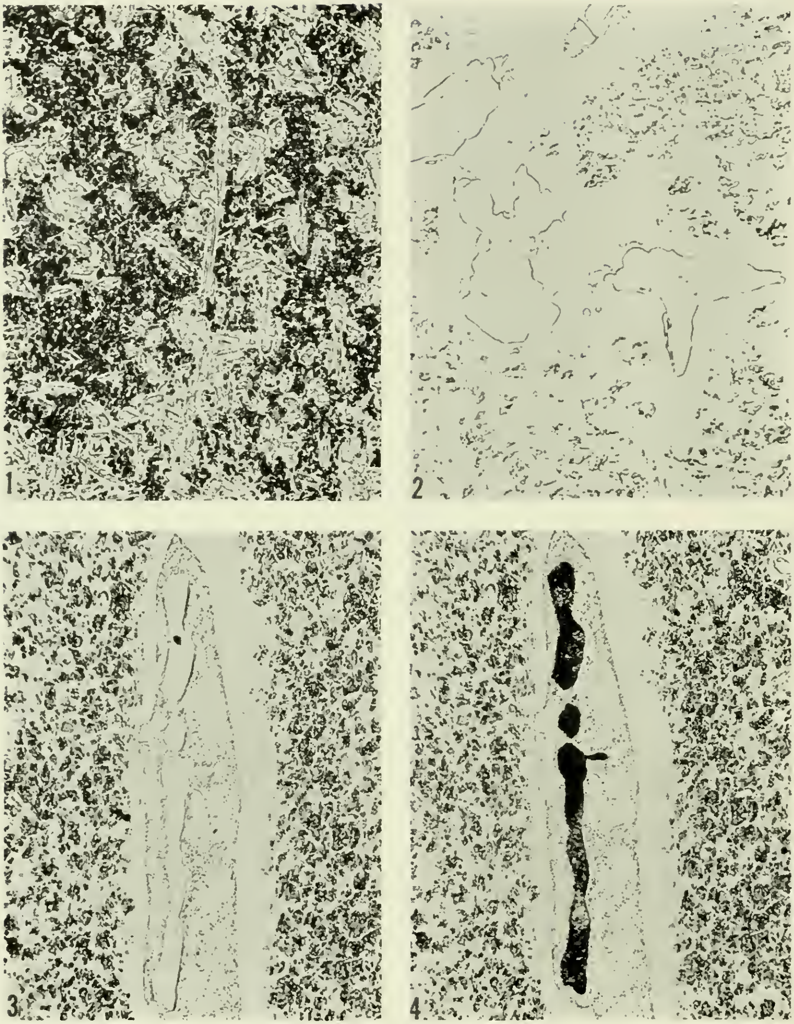
2. SMITHLAND. The same structure, 40 seconds picral; × 150. The structure could not be well established at any higher magnification, though other etchants were used, including nitric-acetic acid, which caused heavy pitting in the kamacite particles. The appearance suggests an undercooled gamma structure, resulting from relatively rapid cooling to a range where diffusion was sluggish, producing a fine dispersion of alpha particles.

3. BABB'S MILL (Troost iron), Kentucky; nickel-rich ataxite, Ni-Co 18.97 percent. The general structure, with a kamacite needle. Picral 45 seconds; × 60. American Museum of Natural History.

4. BABB'S MILL. The same structure at high magnification; an irregular paraeutectoid of taenite in kamacite, the taenite slightly darkened by reason of supersaturation. Picral 25 seconds; × 600.



SMITHLAND AND BABB'S MILL METEORITES.



Klondike Meteorite.

Plate 27

1. Klondike, Yukon, Canada; nickel-rich ataxite; Ni-Co 19.11 percent. General structure, kamacite bodies in a dense, inperfectly granular groundmass. The minute kamacite spindles and needles are thickly disseminated, almost invariably inclosing droplike inclusions of phosphide eutectic. Occasionally the needles are long and thin and a few reach a considerable size, large enough to extend across a field of the size and magnification of this figure. Picral 25 seconds; × 60. U. S. National Museum.

2. Klondike. Part of the groundmass with four minute kamacite bodies. The predominant clear white is taenite. The kamacite shows slight darkening from gamma admixture. The plessitic areas show an aggregate of kamacite particles in taenite, the kamacite particles scanty, minute, and irregularly scattered. Picral 5 seconds; × 600.

3. Klondike. One of the larger kamacite spindles at higher magnification, with iron-phosphide eutectic inclusions, surrounded by taenite which merges with the taenite of the groundmass. The kamacite shows some admixture of minute gamma particles. The pattern of the groundmass suggests granulation, perhaps owing to phantom boundaries of forme gamma grains. Picral 25 seconds; × 120.

4. Klondike. The same area as figure 3, with additional sodium-picrate etching. The iron-phosphide areas are blackened, but the rest of the structure is unaffected. Picral 25 seconds and neutral sodium picrate; × 120.

PLATE 28

1. **MORRADAL**, Norway; nickel-rich ataxite; Ni-Co 19.95 percent. The general structure of the iron is a very fine gamma-alpha paraeutectoid. Groups of kamacite needles, as shown here, are exceptional; the groundmass usually is uniform with no inclusions. Picral 20 seconds; × 60. U. S. National Museum.

2. **MORRADAL.** Typical area of groundmass at high magnification. A regular paraeutectoid structure is fully developed, the gamma phase predominating. The taenite is slightly darkened because of supersaturation. Picral 10 seconds; × 600.

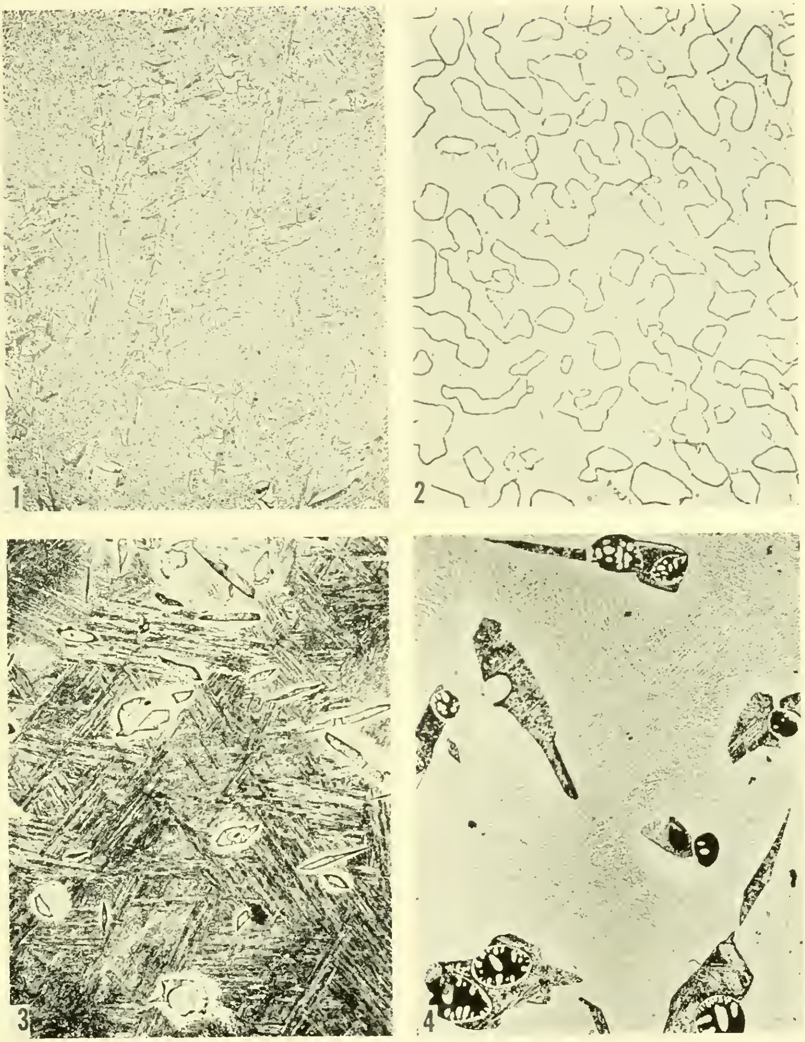
3. **FREDA**, North Dakota; nickel-rich ataxite; Ni-Co 24.15 percent. General structure, a very fine acicular groundmass in which are scattered abundant spindles and irregular inclusions of kamacite, many of which enclose rounded particles of iron-phosphide eutectic.

The acicular groundmass is analogous to the transformation structures in numerous octahedrites. A tentative explanation of its origin might be the following: Owing to the high-nickel content the gamma-alpha transformation was depressed to the neighborhood of 350°, the rate of cooling being very slow. At that point the transformation began, the primary separation of kamacite occurring in many places around previously separated phosphide bodies. After the initial transformation the remaining gamma solid solution underwent only a partial transformation, the kamacite being very sparingly precipitated on octahedral planes, producing the acicular structure. This may have been due to, or preserved by, more rapid cooling from that point downward. Such an origin, as well as the final structure, would be analogous to that of iron-carbon martensite in artificial irons.

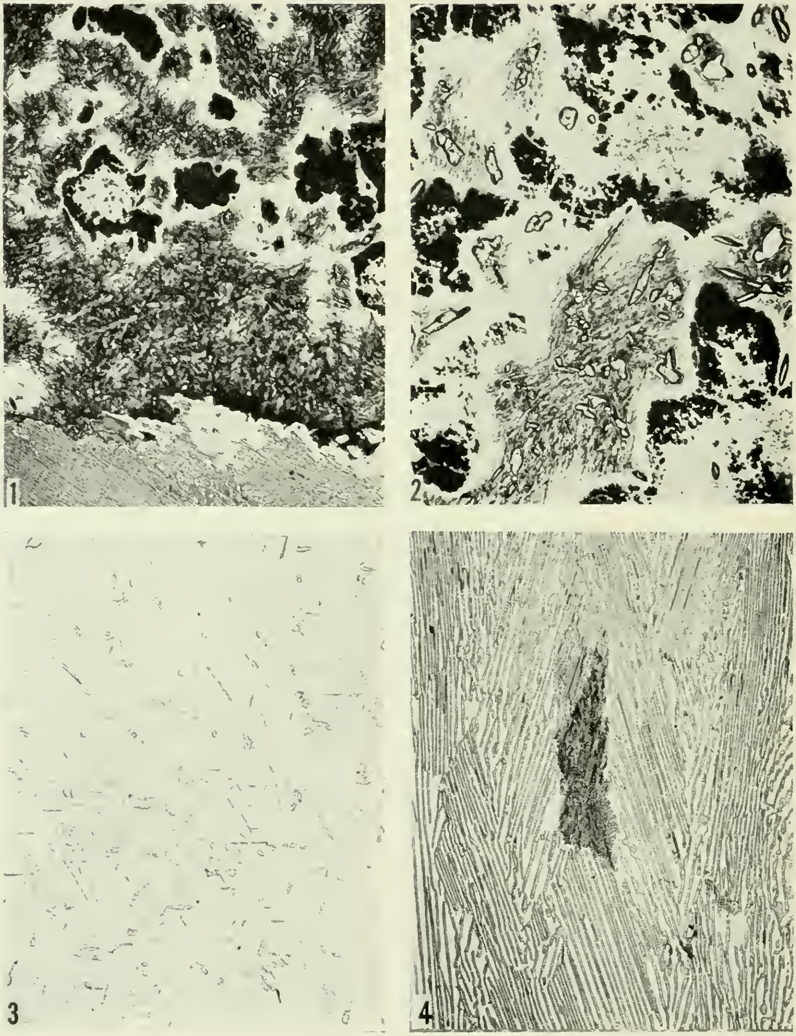
The kamacite bodies are without the taenite borders common in high-nickel ataxites, but are surrounded by considerable areas of taenite, which appear clear. These might be termed areas of kamacite impoverishment, the kamacite segregations having absorbed in their growth all the alpha phase in the vicinity.

Picral 25 seconds; × 60. U. S. National Museum.

4. **FREDA.** The structure shown in figure 3; very light picral and sodium picrate; × 150. The minute inclusions are shown to be phosphide eutectic, the excess of iron having been rejected in minute clear drops. The kamacite bodies themselves show a considerable phosphide content.



MORRADAL AND FREDA METEORITES.



San Cristobal Meteorite.

PLATE 29

1. SAN CRISTOBAL, Chile; nickel-rich ataxite; Ni-Co 26.60 percent. The nickel content of this iron is close to the saturation ratio for kamacite in taenite. It therefore consists almost wholly of taenite, with vestiges of ataxite structure. A number of areas of a perfect pearlitic pattern are the outstanding feature of this extraordinary meteorite. The photograph shows the general structure of the mass—a ground of clear taenite, with areas of an acicular structure enclosing minute kamacite bodies, and black areas of an ultramicroscopic gamma-alpha aggregate analogous in structure to sorbite and troostite in steel. Below is part of a pearlitic area. The iron etches slowly. Picral 75 seconds; × 30. American Museum of Natural History.

2. SAN CRISTOBAL. Part of the general structure at higher magnification. The structure of the acicular areas is more apparent. Many of the kamacite particles contain minute inclusions of iron-phosphide eutectic. The black sorbiticlike areas are unresolved. Picral 75 seconds; × 60.

3. SAN CRISTOBAL. Part of an acicular area with very light etching, showing only the kamacite bodies which have some octahedral orientation, The structure of the groundmass does not appear. Picral 20 seconds; × 60.

4. SAN CRISTOBAL. Part of an area of gamma-alpha pearlitic paraeutectoid. A small finely lamellar area is surrounded by a coarser structure. Picral 20 seconds; × 30.

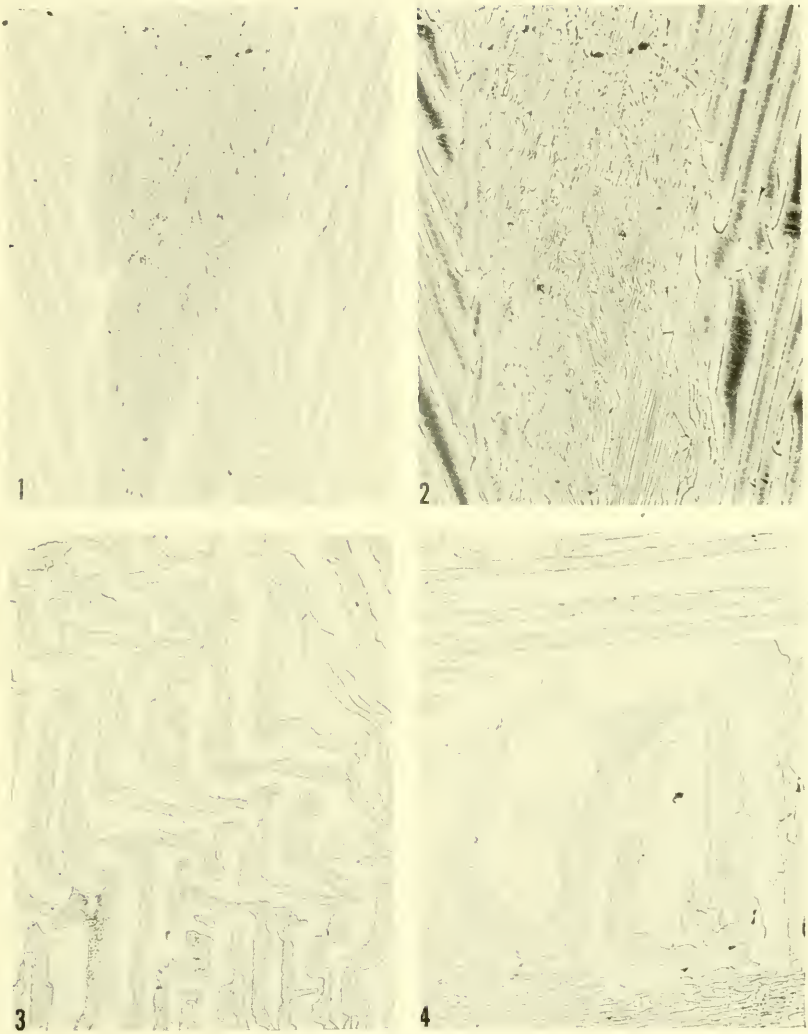
PLATE 30

1. SAN CRISTOBAL. The fine area shown in the center of plate 29, figure 4, etched very lightly. The kamacite lamellae are gray. Picral 20 seconds; × 150. American Museum of Natural History.

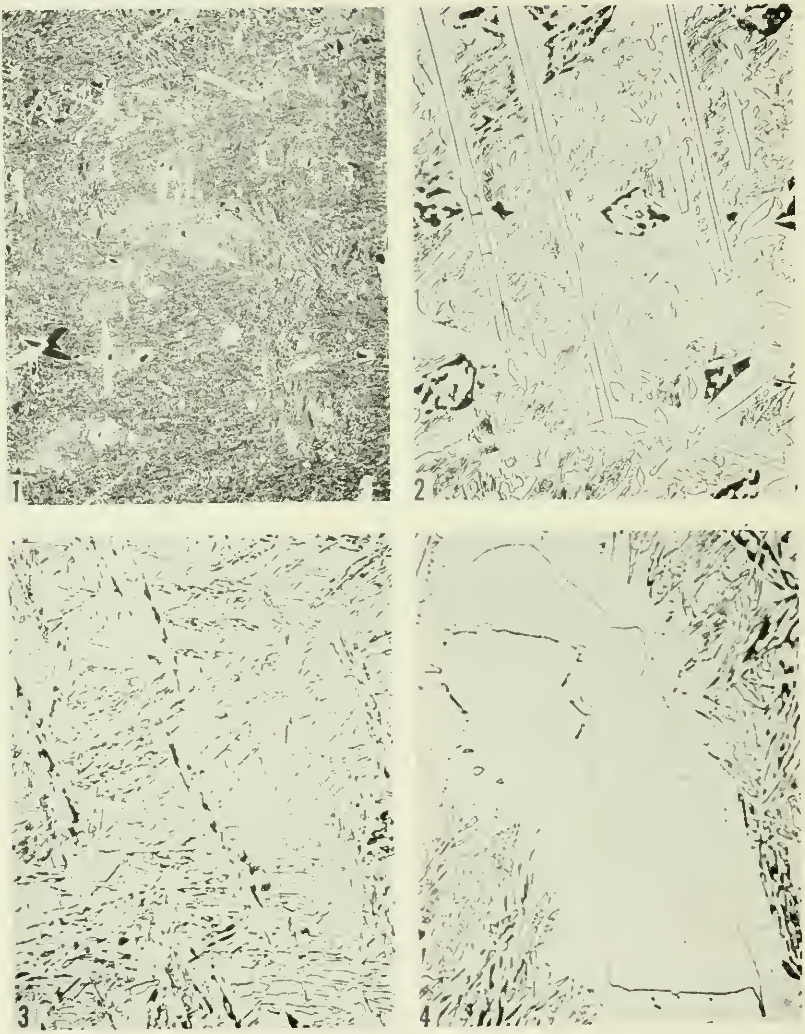
2. SAN CRISTOBAL. The identical area shown in figure 1. With stronger etching the lights and shades are reversed; the kamacite lamellae are now clear (probably because of a film of cold-worked metal caused by polishing, which was removed by the longer etching), while the slightly supersaturated taenite lamellae are darkened. Picral 50 seconds; × 150.

3. SAN CRISTOBAL. A local variation in the pearlitic pattern. With light etching the kamacite is gray. Vestiges of octahedral orientation. Picral 20 seconds; × 150.

4. SAN CRISTOBAL. Another local variation in pearlitic pattern; coarse irregular lamellae, with orientation, adjoining an area of regular structure.



SAN CRISTOBAL METEORITE.



Limestone Creek Meteorite.

PLATE 31

1. LIMESTONE CREEK, Alabama; nickel-rich ataxite; Ni-Co 30.47 percent. This extraordinarily high-nickel iron is surpassed in nickel content only by Santa Catharina and Octibbeha County. Its two-phase gamma-alpha structure is irregular. Despite its high nickel content, it contains in places a profusion of kamacite needles (lamellae), sometimes regularly oriented. The photograph shows such needles, which appear larger than they are because surrounded by areas of clear taenite. Picral 20 seconds; × 60. Field Museum of Natural History.

2. LIMESTONE CREEK. An example of oriented needles. The taenite, strongly predominating in the groundmass, does not form borders around the needles, as in lower nickel ataxites, but forms a clear homogeneous field in which the needles and particles lie. The black spots are oxidized kamacite. Picral 10 seconds; × 600.

3. LIMESTONE CREEK. An example of the more irregular two-phase structure. Kamacite shows considerable oxidation. Picral 10 seconds; × 600.

4. LIMESTONE CREEK. One of the larger kamacite bodies, in an area of taenite, surrounded by oxidized groundmass. Picral 10 seconds; × 600.

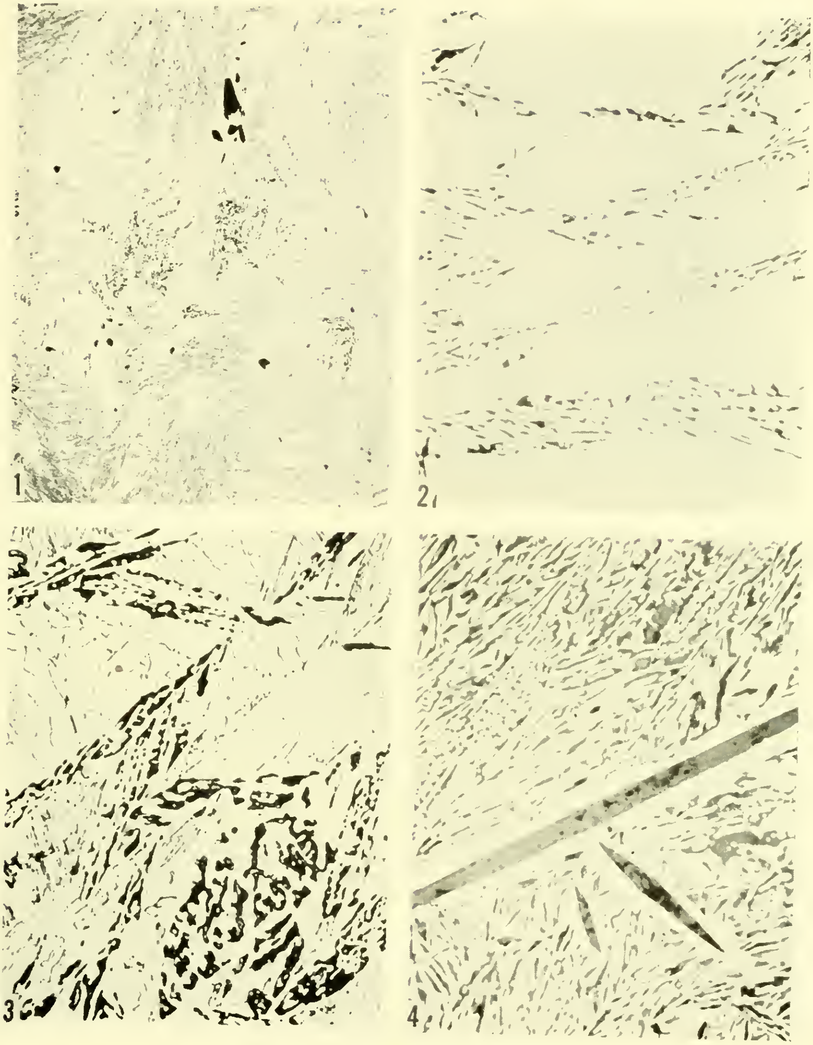
Plate 32

1. Limestone Creek. Structure in the central part of the slice examined. Unetched; × 60. The gray component, though it might appear too gray for oxide, is shown in the next photograph to be such. Field Museum of Natural History.

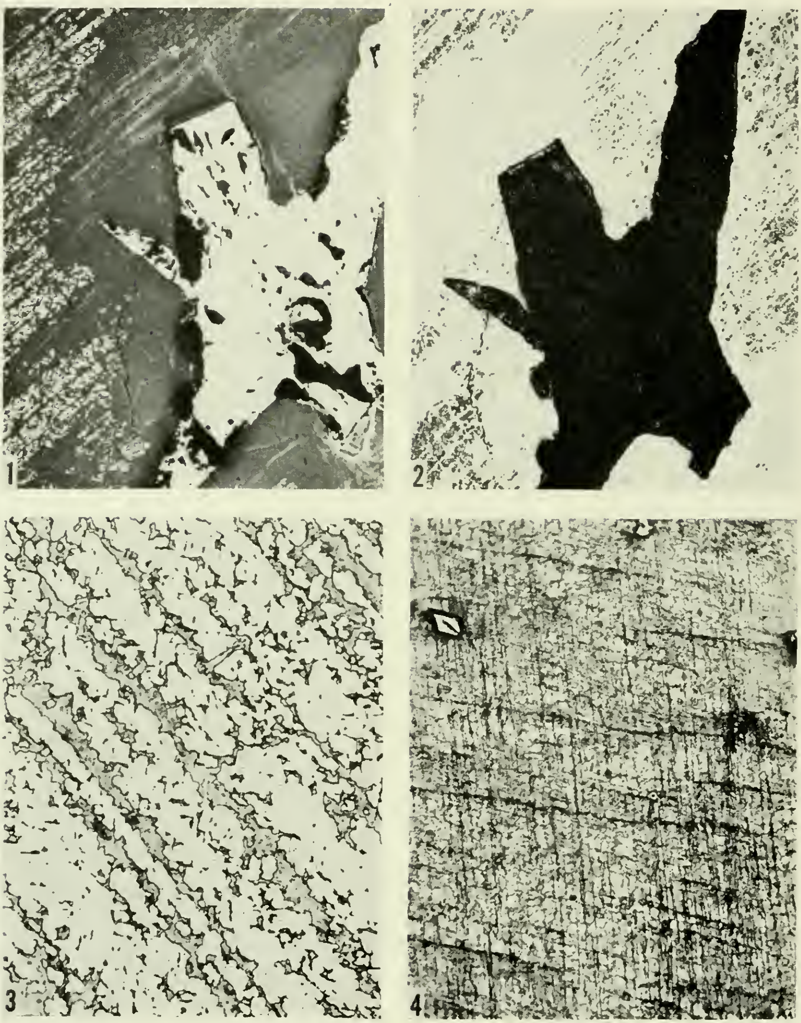
2. Limestone Creek. Part of the area shown in figure 1 at high magnification. The gray component in figure 1, appearing in delicate branching forms, is here seen to be oxidized kamacite particles. The groundmass shows no structure. Unetched; × 600.

3. Limestone Creek. An area somewhat similar to figure 2. Light etching develops the two-phase structure of the groundmass, the gamma phase predominating, the alpha (kamacite) areas in part oxidized. Picral 10 seconds; × 600.

4. Limestone Creek. At this place, near the edge of the slice, oxidation was stronger than in the preceding figures. The needles of kamacite though surrounded by taenite are darkened, as well as the kamacite of the groundmass. Unetched; × 600.



LIMESTONE CREEK METEORITE.



Santa Catharina Meteorite.

Plate 33

1. Santa Catharina, Brazil; nickel-rich ataxite; Ni-Co 34.45 percent. The microstructure of this specimen is unique, a very regular pattern of strongly oriented mottled bands of darker and lighter color. The latter show a phosphide content with picrate etching, and disappear in the vicinity of schreibersite inclusions. The mottled bands at the left are part of the prevalent structure of the entire mass. The dark area surrounding the large schreibersite inclusion is structureless. Similar areas surround all schreibersite inclusions, large and small. Picral 50 seconds; × 30. Harvard University.

2. Santa Catharina. Area shown in figure 1 with additional etching with neutral sodium picrate. The large schreibersite inclusion is blackened and the light component darkens, indicating a phosphide content.

3. Santa Catharina. Typical area of mottled bands. Same specimen as the preceding. Picral 25 seconds; × 150.

4. Santa Catharina. In this specimen the mottled banded structure is much less distinct, being largely replaced by the confused striated pattern here shown. It is to be noted, however, that this pattern, like the mottled bands in the Harvard specimen, disappears around the rhabdites. Picral 30 seconds; × 60. U. S. National Museum.

Santa Catharina consists essentially of taenite and presumably is wholly in the gamma phase. Although it has been thought by many to be of terrestrial origin, the presence of troilite and schreibersite, neither of which is found in terrestrial rocks, seems conclusive as to its nature.

The analysis of Damour (1877) gives: Fe 63.69; Ni 33.97; Co 1.48; P 0.05; C 0.20; S 0.16; Si 0.01. No other analysis is available. In view of the frequent occurrence of schreibersite, and the presence of phosphide in the structural pattern, the above percentage of phosphorus seems low.

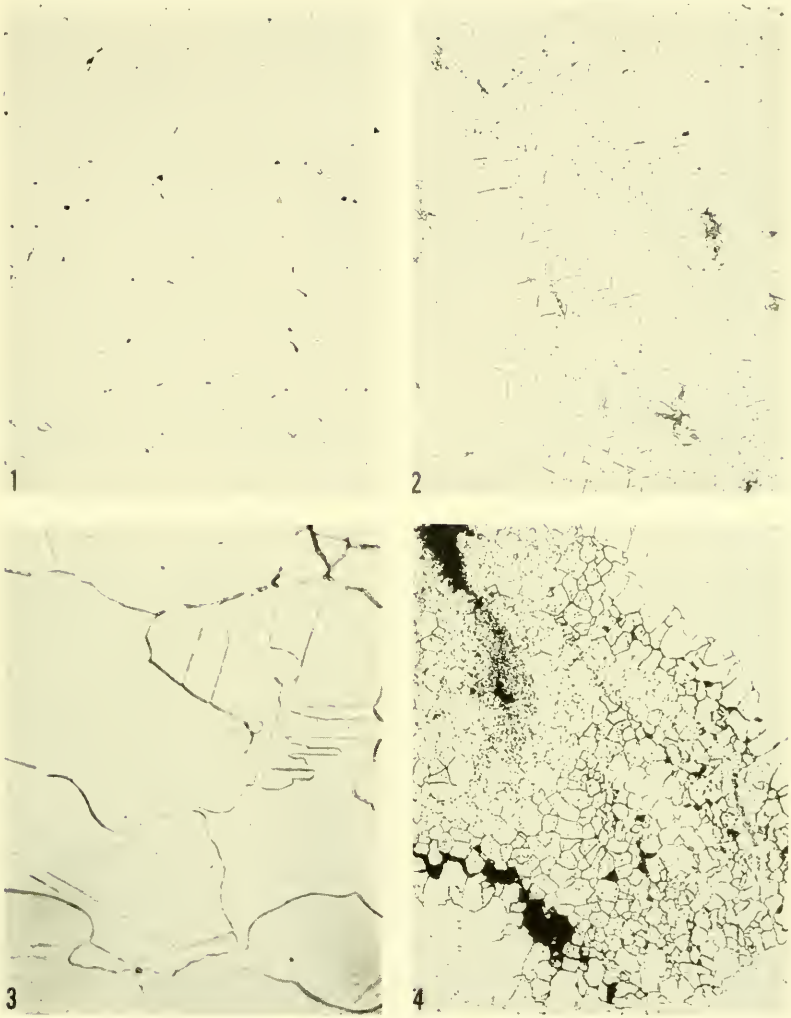
PLATE 34

1. OCTIBBEHA COUNTY, Mississippi; nickel-rich ataxite; Ni-Co 62.73 percent. This meteorite, unique because of its extraordinary nickel content, was found in an Indian mound, the mass weighing only 155 grams, of which half was lost. Its authenticity has been doubted by Cohen and others, and it was not included by Farrington among North American meteorites. The presence of rhabdites, shown in this photograph, seems definitely to establish its character. Unetched; × 60. American Museum of Natural History.

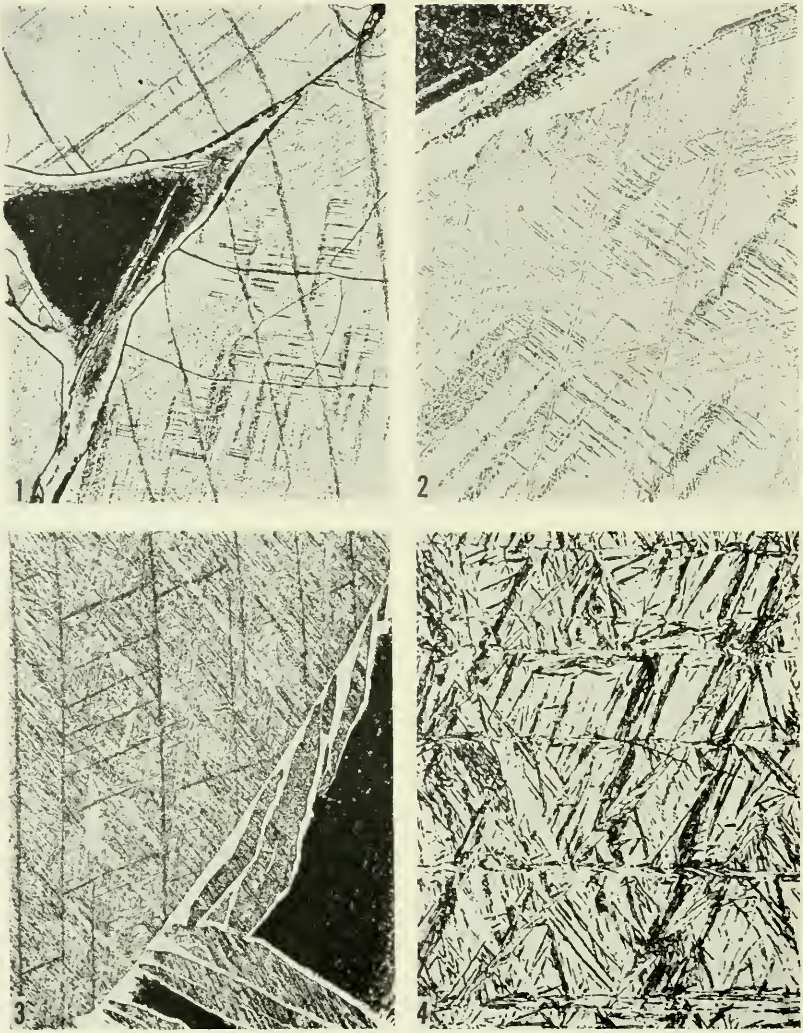
2. OCTIBBEHA COUNTY. The short needles are not inclusions but etching pits, apparently forming along gamma twinning planes. The nature of the irregular inclusions is obscure. Although they resemble phosphorus-enriched areas they do not darken with neutral sodium picrate etching, and several etchants for carbides were tried without results. They are apparently metallic, owing perhaps to undetermined impurities. Nitric-acetic acid 180 seconds; × 60. Harvard University.

3. OCTIBBEHA COUNTY. The grains show characteristic gamma twinning. Nitric-acetic acid 300 seconds; × 600.

4. OCTIBBEHA COUNTY. The intergranular invasion of hydroxide reveals clearly a grain structure, which was not brought out by etching. Nitric-acetic acid 60 seconds; × 60.



Octibbeha County Meteorite.



Trenton, Thunda, and Canton Meteorites.

Plate 35

1. Trenton, Wisconsin; medium octahedrite; Ni-Co 7.73 percent (1869). The heavy widely spaced lines, as well as the finer and shorter ones, might be mistaken for Neumann lines, but they are due to a transformation structure; see figure 2. With heavy etching the dense plessite is black, but much of it is black and unresolved even with much lighter etching, except at very high magnification. Picral 50 seconds; × 60.

2. Trenton. A portion of the area shown in figure 1. The upper left corner of this photograph is at about the center of the right side of the plessite field in figure 1. With higher magnification the resemblence to Neumann lines disappears. The lighter etching does not show the grain boundaries in figure 1. Very light picral etch; × 150.

3. Thunda, Australia; medium octahedrite; Ni-Co 9.05 percent. The kamacite, both in the band (upper left) and within the plessite field, shows a characteristic gamma-alpha transformation structure. Picral 50 seconds; × 60. American Museum of Natural History.

4. Canton, Georgia; coarsest octahedrite; Ni-Co 7.20 percent. This iron consists almost wholly of kamacite, which throughout shows an extraordinary development of the gamma-alpha transformation structure, the result of rapid cooling in the gamma-alpha range, resembling the martensitic Fe-C structure in artificial irons though much coarser. Picral 30 seconds; × 150.

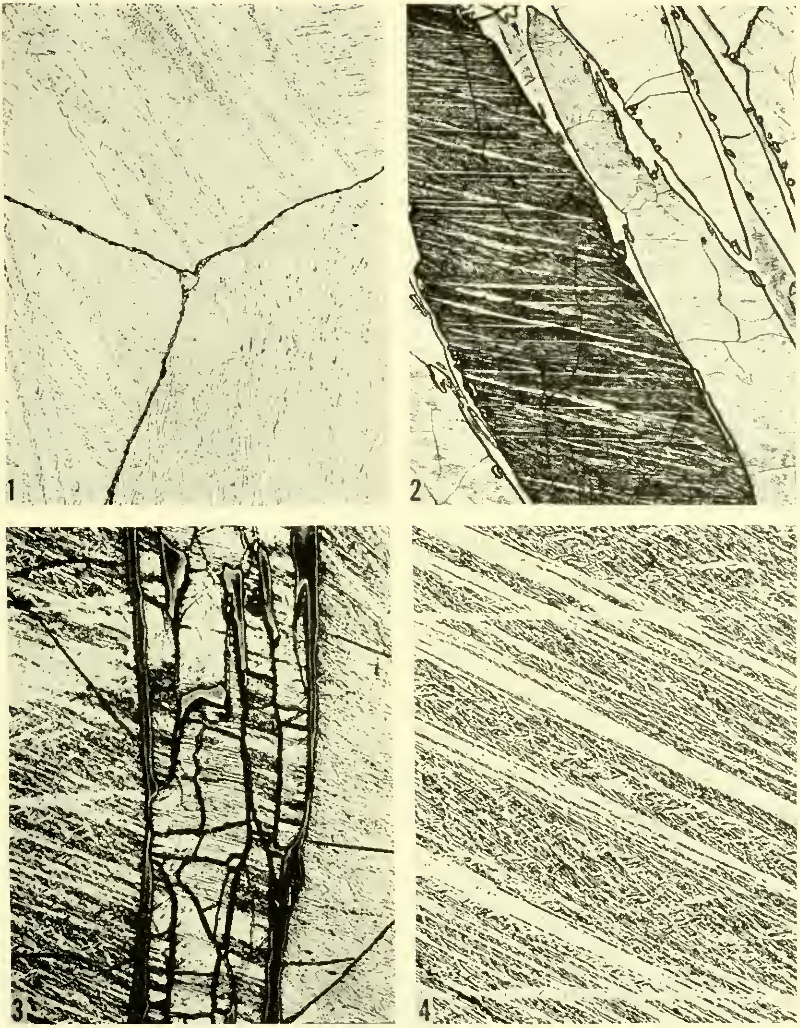
Plate 36

1. Smith's Mountain, North Carolina; fine octahedrite; Ni-Co 8.52 percent. Granular kamacite showing a transformation structure of varying character in the three grains. The structure at lower right resembles a martensitic iron-carbon structure in a low carbon (e. g., 0.10 percent) steel water-quenched from the lower gamma-alpha range. Picral 45 seconds; × 150. U. S. National Museum.

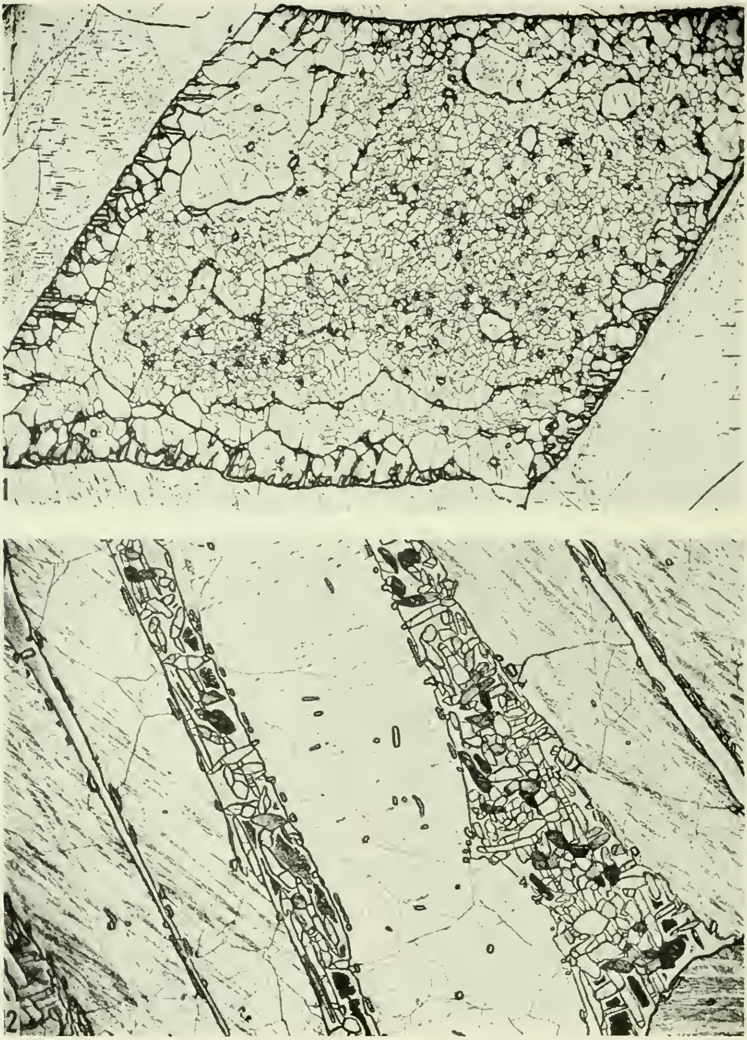
2. Bear Creek, Colorado; fine octahedrite; Ni-Co 7.88 percent (Jackson, 1867). Part of a rounded "swollen" kamacite band with strongly marked transformation structure—an example of the "hatched" kamacite of the older writers. Traces of the structure appear in the kamacite bands on each side. Picral 75 seconds; × 30.

3. Kenton County, Kentucky. Medium octahedrite; Ni-Co 8.49 percent. The kamacite shows varying forms of transformation structure. The irregular taenite lamellae are dark by reason of incomplete transformation. Picral 25 seconds; × 150.

4. Kenton County. Structure similar to that in the left portion of figure 3. The pattern is very regularly oriented. Picral 25 seconds; × 150.



SMITH'S MOUNTAIN, BEAR CREEK, AND KENTON COUNTY METEORITES.



Kenton County and Bear Creek Meteorites.

PLATE 37

1. KENTON COUNTY, Kentucky; medium octahedrite; Ni-Co 8.49 percent. A field of coarsely granular plessite. Boundaries of large gamma grains both in the field and in the surrounding kamacite. Owing to strong etching there is sharp blackening around the kamacite grains, and around the small taenite threads at the edges of the field. Picral 60 seconds; × 30.

2. BEAR CREEK, Colorado; fine octahedrite; Ni-Co 7.88 percent (1867). Lamellae of taenite and fields of coarse granular plessite separating kamacite bands. As is the case with most coarse plessite, especially in irons showing transformation structure, there is little or no taenite bordering the fields, indicating relatively rapid formation at a temperature at which diffusion was active. Even with strong etching taenite is only slightly darkened, indicating fairly complete transformation. All the kamacite bands show more or less transformation structure, producing parallel lines somewhat resembling Neumann lines. Small schreibersite bodies are close to the taenite lamellae.

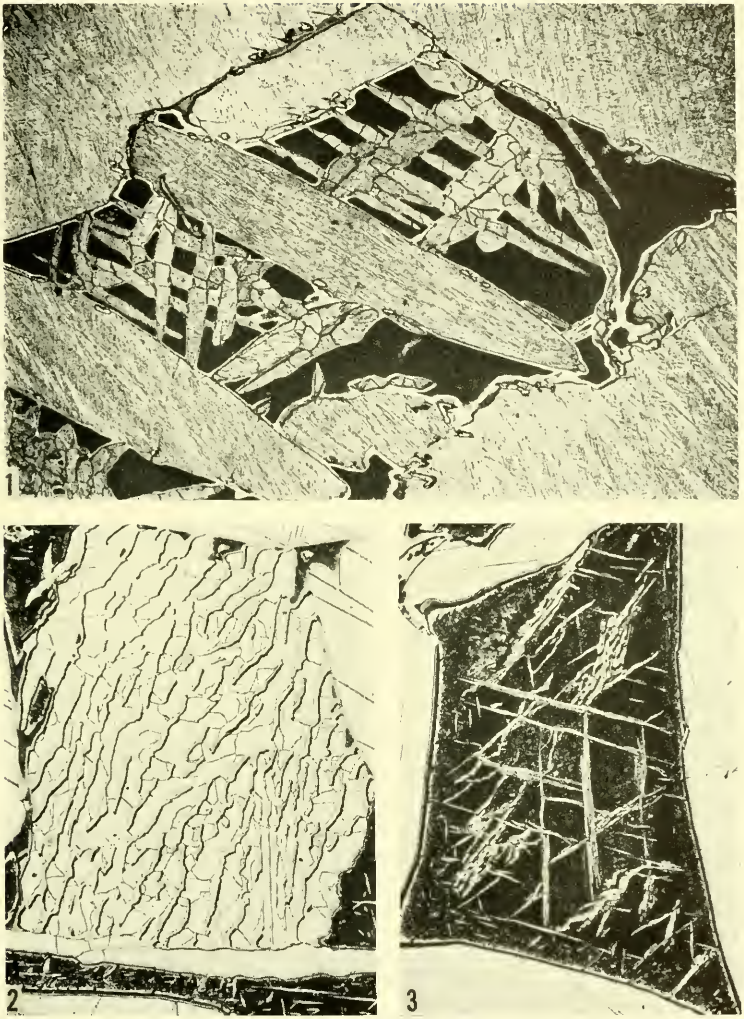
Such plessite fields, common in the coarser octahedrites, are unusual in fine ones. Bear Creek is necessarily classed as fine because the bands have a quite uniform width of slightly less than 0.5 mm.; but in all its structural features it resembles a medium octahedrite. Analyses by Smith (1867) and by Jackson (1867) give respectively 14.89 and 7.88 percent Ni-Co. The former percentage is obviously impossible, but the latter would be consistent with the structure. Picral 75 seconds; × 30.

PLATE 38

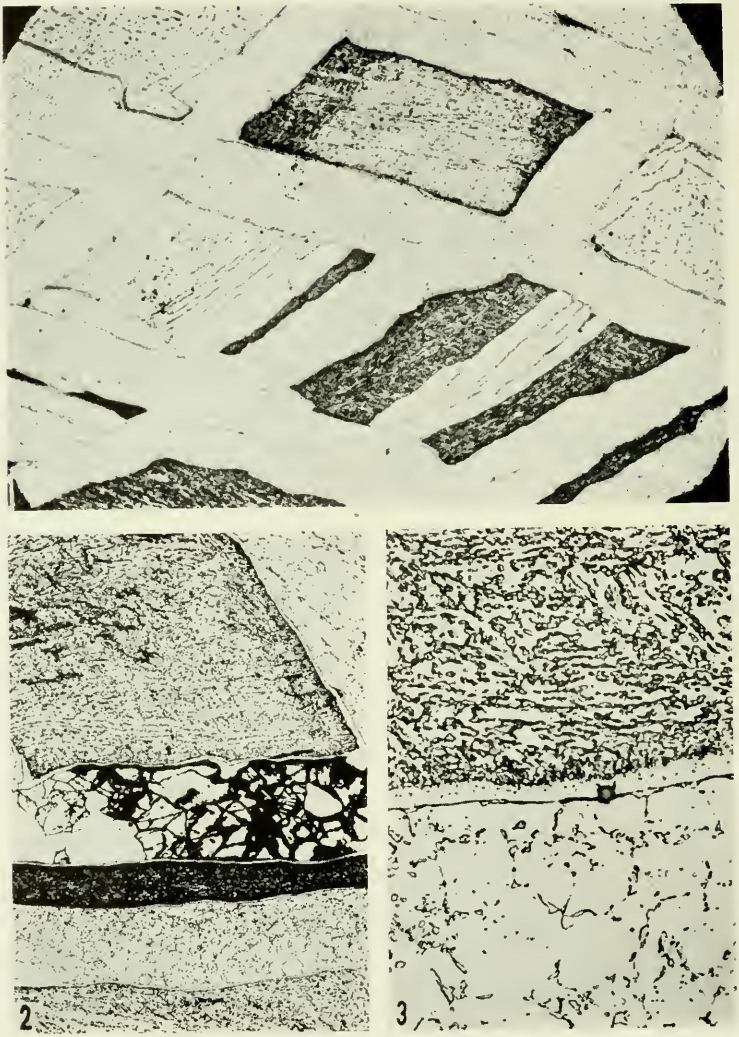
1. SMITH'S MOUNTAIN, North Carolina; fine octahedrite; Ni-Co 8.52 percent. A coarse plessite field at moderate magnification. With strong etching the dense plessite appears black but is not wholly so with lighter etching. The kamacite lamellae reflect the orientation of the general pattern. All kamacite shows an acicular gamma-alpha transformation structure. Taenite borders are scanty. Picral 80 seconds; × 30. U. S. National Museum.

2. SEELÄSGEN, Prussia; coarsest octahedrite; Ni-Co 5.84 percent. Plessite field filled with coarse irregular taenite lamellae. Near the edges are taenite areas dark because of supersaturation. The Ni-Co percentage of this iron, given in an old analysis (1848), is almost certainly too low. Picral 60 seconds; × 60.

3. SEELÄSGEN. A field of dense plessite with octahedrally oriented needles (lamellae) of kamacite. Small curved schreibersite inclusion at upper left. The dense plessite is formed by the low temperature transformation of a nickel-rich area, resulting in a structure of extremely fine kamacite particles embedded in the transforming taenite. Picral 60 seconds; × 60.



Smith's Mountain and Seeläsgen Meteorites.



WOOD'S MOUNTAIN METEORITE.

PLATE 39

1. WOOD'S MOUNTAIN, North Carolina; finest octahedrite; Ni-Co 8.61 percent. The nickel-cobalt content is low for a finest octahedrite. An area at moderate magnification showing an unusual variety of plessite fields. The general pattern of the iron is a regular network of kamacite bands with very thin taenite lamellae. Light picral; × 30.

2. WOOD'S MOUNTAIN. Areas from below upward—(a) light plessite field; (b) band of granular kamacite; (c) band of dense plessite with tenuous taenite border; (d) kamacite band with intergranular invasion of hydroxide; (e) light plessite field showing oriented bands. Light picral; × 45.

3. WOOD'S MOUNTAIN. A portion of areas (b) and (c) in figure 2 at high magnification. The granulated kamacite band (below) shows a profusion of minute droplike bodies of taenite along the grain boundaries. In the dense plessite band (above) the crowded taenite particles show a tendency to orientation. Very light picral; × 600.

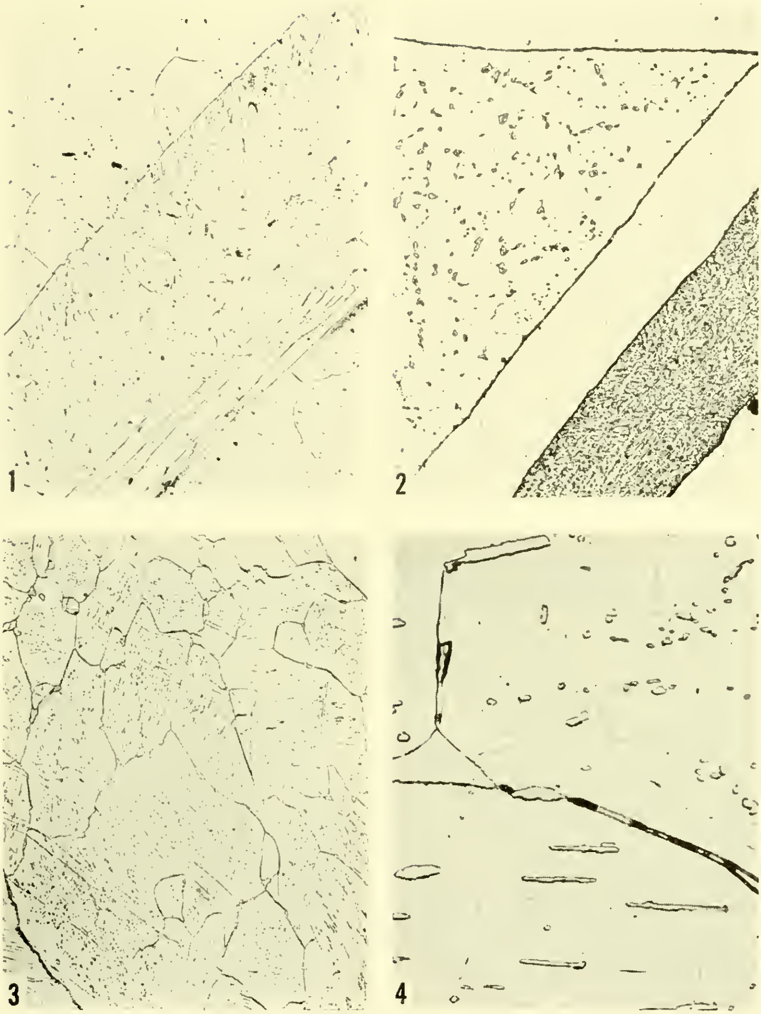
PLATE 40

1. ROEBOURNE, Australia; medium octahedrite; Ni-Co 8.92 percent. A light plessite field, consisting of clear kamacite with a sparse distribution of taenite particles, between granulated kamacite bands. The grain boundaries of the bands do not penetrate the field, which has its own system of grains. Several taenite lamellae on lower side of field, but no taenite border on upper side. Picral 60 seconds; × 60.

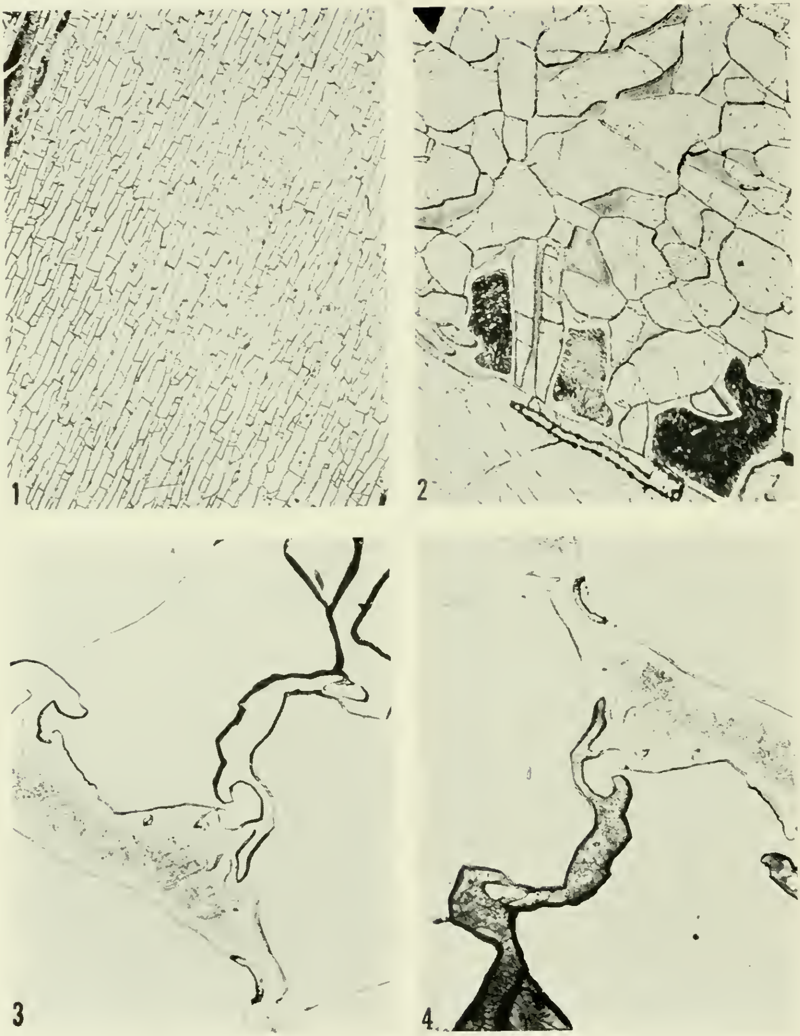
2. SAN FRANCISCO MOUNTAINS, Arizona; finest octahedrite; Ni-Co 7.99 percent. The nickel-cobalt content is very low for a finest octahedrite. A very light plessite field consisting of clear kamacite with droplike segregations of taenite along grain boundaries. Nital 10 seconds; × 60.

3. SAN FRANCISCO MOUNTAINS. A light plessite field, consisting of clear granulated kamacite with minute needles and particles of taenite diversely oriented. Some grains show Neumann lines. Picral; × 60.

4. SAN FRANCISCO MOUNTAINS. Part of an area similar to figure 3 at high magnification, showing taenite needles (sections of flakes) and irregular particles. This area is in the zone of alteration; Neumann lines are obliterated and there is a faint pattern of secondary granulation. The outlines of the original larger grains are marked by larger taenite bodies. The analysis of this iron shows no phosphorus. Picral 3 minutes; × 600.



ROEBOURNE AND SAN FRANCISCO MOUNTAINS METEORITES.



CLEVELAND, SMITH'S MOUNTAIN, AND PINE RIVER METEORITES.

PLATE 41

1. CLEVELAND, Tennessee; medium octahedrite; Ni-Co 9–10 percent. Part of a large field of very uniform lamellar plessite. Picral 50 seconds; × 45.

2. SMITH'S MOUNTAIN, North Carolina; fine octahedrite; Ni-Co 8.52 percent. An area of coarse granulated plessite. The kamacite granules show the same transformation structure as the adjacent kamacite band. Taenite bodies are more or less gray by reason of supersaturation. In the larger taenite areas transformation is incomplete, leaving cores of a dense unresolved gamma-alpha mixture. Picral 45 seconds; × 150. U. S. National Museum.

3. PINE RIVER, Wisconsin. An iron to be described by E. P. Henderson and the author, which may be provisionally classified as an atypical coarsest octahedrite with accessory silicates. A plessite field with a narrow taenite border. Upper right, a large irregular inclusion of schreibersite. Light picral; × 60.

4. PINE RIVER. The same area as figure 3 with additional etching 5 minutes with neutral sodium picrate. The shaded core is unaffected, indicating that it does not contain phosphide, but is a gamma-alpha aggregate. The schreibersite inclusion is darkened. (The position of figure 4 is reversed.)

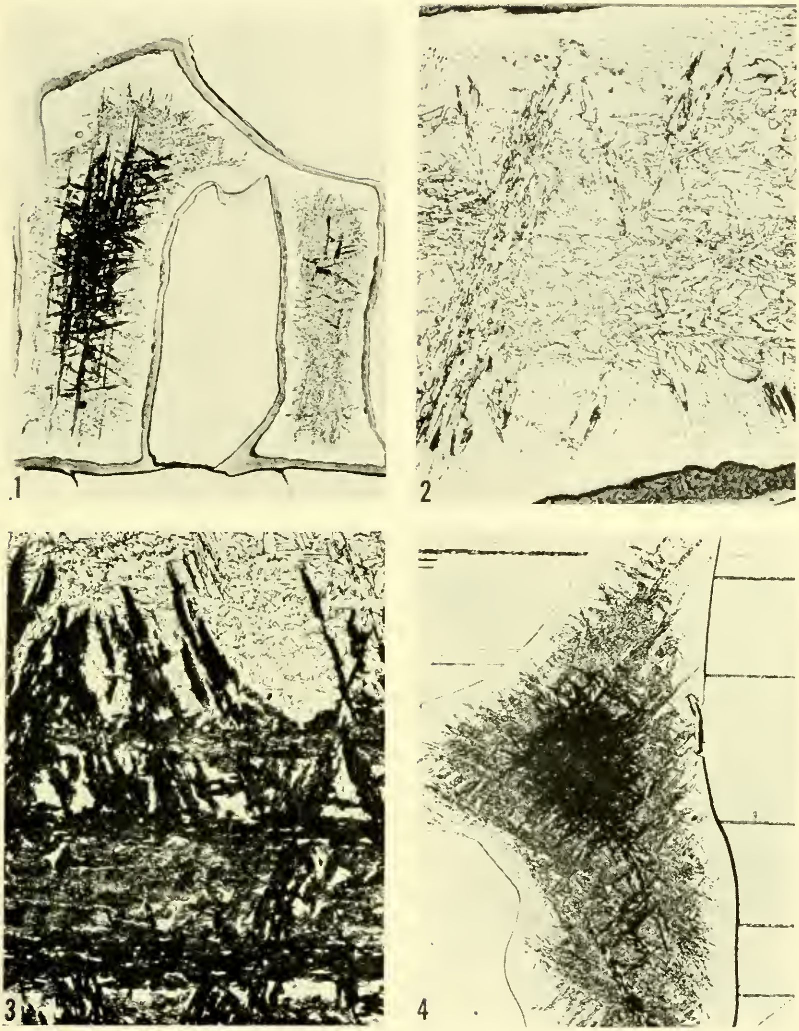
PLATE 42

1. PINE RIVER, Wisconsin; an undescribed iron that may be provisionally classified as an atypical coarsest octahedrite with accessory silicates. A field of plessite showing incomplete transformation, bordered by taenite which is gray by reason of supersaturation. The acicular structure, oriented on octahedral (gamma) planes, is composed of a gamma-alpha aggregate. It is unchanged with picrate etching. The separation of the two phases is more complete in the right portion; in the left portion, which is larger, more of the dense untransformed aggregate was trapped in the interior. Light picral; × 60.

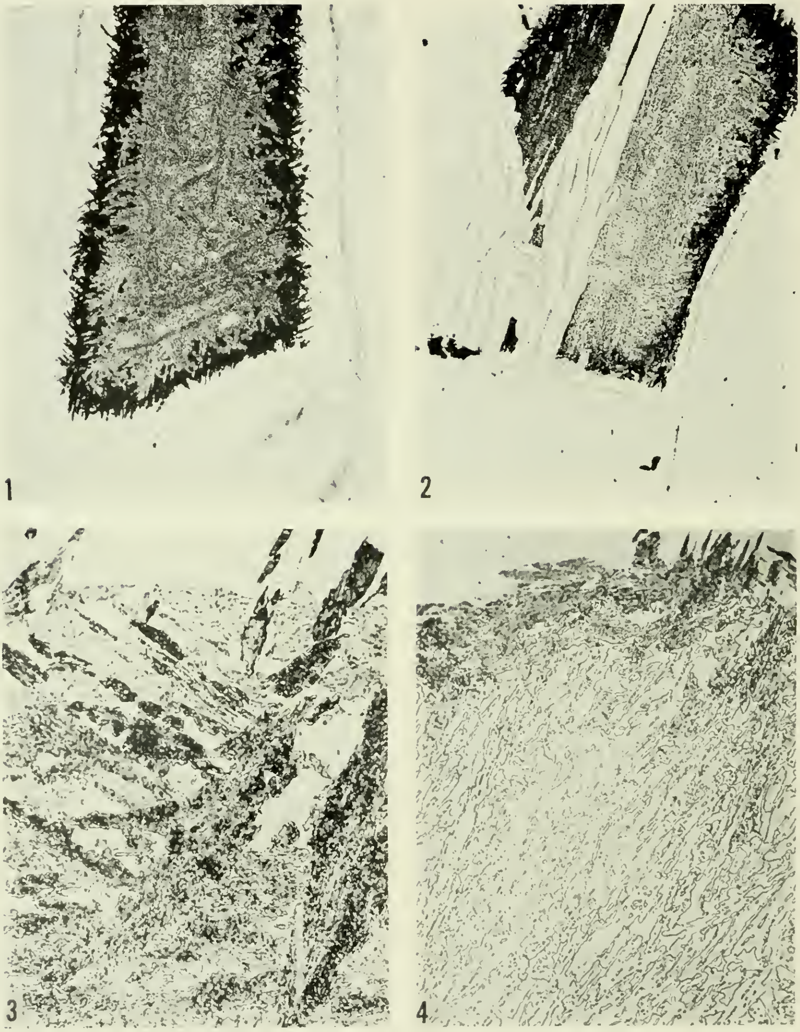
2. PINE RIVER. Part of the right portion of the field in figure 1. An imperfectly developed paraeutectoid structure has been attained, resembling that in a number of nickel-rich ataxites. Near the taenite border the gamma phase has been absorbed, leaving clear kamacite. Light picral; × 300.

3. PINE RIVER. Part of the left portion of the field in figure 1. The abundant dense gamma-alpha aggregate is mostly unresolved at 1,000 diameters. Light picral; × 300.

4. BARRANCA BLANCA, Chile; listed as a brecciated (more properly granular) octahedrite; Ni-Co 8.66 percent. An area of taenite with incompletely transformed core. Heavy Neumann lines. Picral 60 seconds; × 60. American Museum of Natural History.



PINE RIVER AND BARRANCA BLANCA METEORITES.



LAURENS COUNTY AND GRANT METEORITES.

PLATE 43

1. LAURENS COUNTY, South Carolina; finest octahedrite; Ni-Co 14.21 percent. Plessite field showing a gamma-alpha aggregate, light in center, with a broad clear taenite border. The variation in structure is apparently due to a concentration gradient, the nickel content being less in the center. Such a gradient has been shown in other irons by quantitative nickel coloration. Picral 25 seconds; × 60. U. S. National Museum.

2. GRANT, New Mexico; medium octahedrite; Ni-Co 9.98 percent. Plessite field, the right part of which is similar to figure 1. The lower left portion consists of lamellae of clear taenite in a groundmass of kamacite, which in places merges with the kamacite of the surrounding mass. Picral 3 to 5 seconds; × 60.

3. GRANT. Part of the darker untransformed structure shown in figure 2. Partly resolved needles (lamellae) of dark gamma-alpha aggregate. Picral 3 to 5 seconds; × 600.

4. GRANT. Part of the lighter area of dense plessite shown in figure 2. Transformation is more complete; elongated particles of taenite (slightly gray because of supersaturation) in a ground of kamacite. Picral 3 to 5 seconds; × 600.

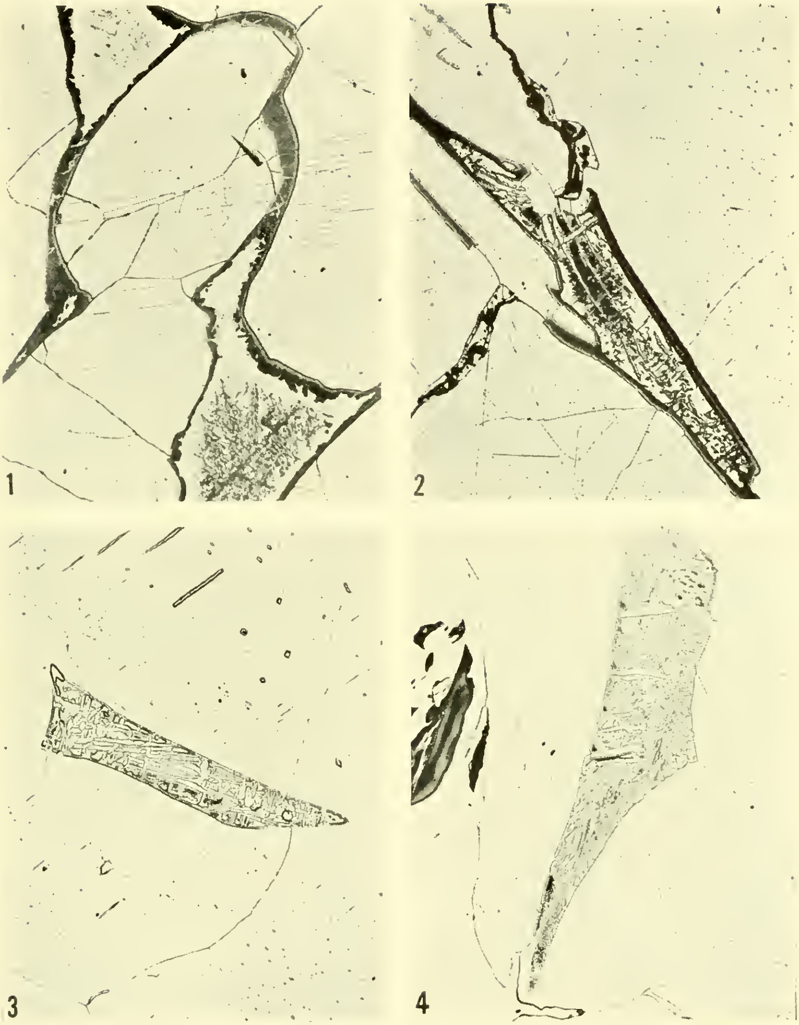
PLATE 44

1. CLEVELAND, Tennessee; medium octahedrite; Ni-Co 9–10 percent. Irregular plessite inclusions. The lamellae of taenites are dark because of supersaturation with respect to kamacite; the triangular areas above and below have incompletely transformed cores with an acicular gamma-alpha structure. Picral 50 seconds; × 60.

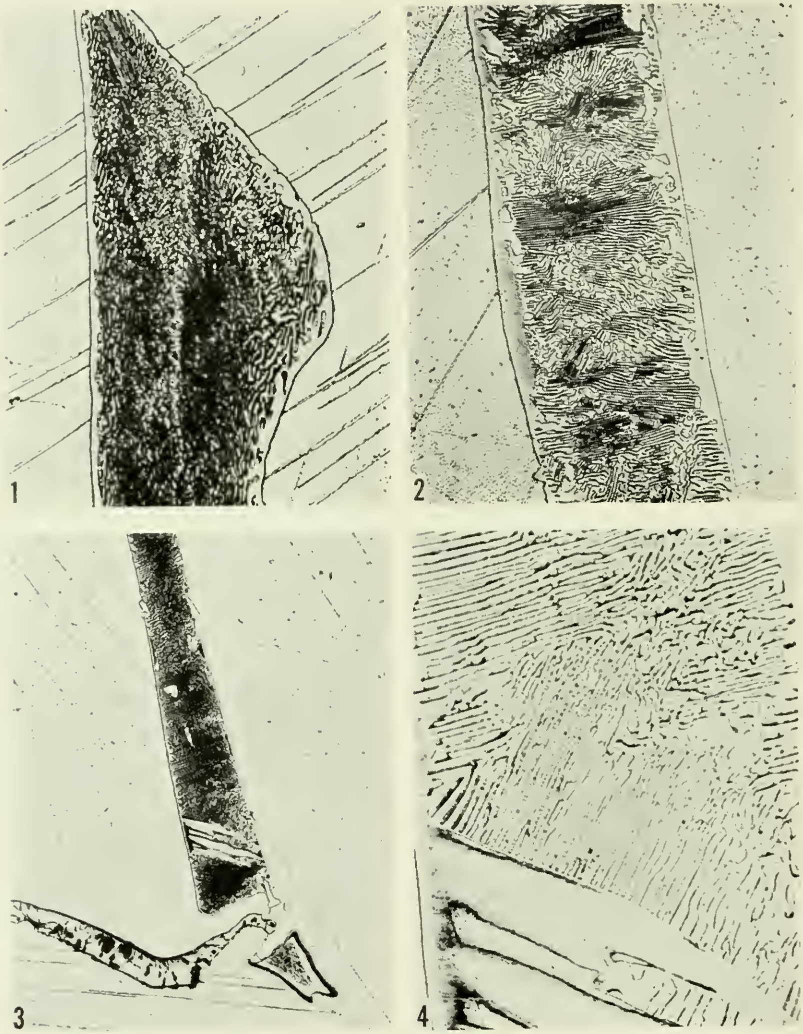
2. ODESSA, Texas; coarse octahedrite; Ni-Co 7.99 percent, P 0.23 percent. Irregular plessite field bordered by dark supersaturated taenite; within, needles of kamacite and a dark untransformed area. Two small clear schreibersite bodies and two irregular larger ones with black marks due to chipping. Nital 10 seconds; × 60.

3. OTUMPA, Argentina; hexahedrite; Ni-Co 5.68 percent. Plessite consisting chiefly of needles and granules of kamacite. Other plessite fields in great variety are found in this iron. Otumpa was classified by Brezina and by Cohen as a nickel-poor ataxite, and it is still so listed in all museums. It is, however, a granular hexahedrite, in many places with a profusion of Neumann lines, which often run parallel through several grains. Rhabdites, and needles and irregular bodies of schreibersite, are abundant. Light picral; × 30.

4. YOUNDEGIN, Australia; coarse octahedrite; Ni-Co 7.01 percent. A plessite field with a well-developed but irregular pearlitic structure. Picral 10 seconds; × 60.



CLEVELAND, ODESSA, OTUMPA, AND YOUNDEGIN METEORITES.



LEEDS, YOUNDEGIN, AND SEELÄSGEN METEORITES.

PLATE 45

1. LEEDS, Quebec; medium octahedrite; no analysis. The specimen, locality unknown, came with other minerals from Leeds and was recognized in 1937. Plessite field showing an imperfect pearlitic pattern. Picral 60 seconds; × 60.

2. YOUNDEGIN, Australia; coarse octahedrite; Ni-Co 7.01 percent. A narrow plessite band with a well-developed pearlitic structure. The taenite border is slightly supersaturated. Picral 3 to 5 seconds; × 300.

3. SEELÄSGEN, Prussia; coarsest octahedrite; Ni-Co 5.84(?) percent; as to composition, see plate 38. A plessite field showing pearlitic structure in figure 2. Picral 60 seconds; × 60.

4. SEELÄSGEN. Part of the area shown in figure 3. At lower left, kamacite needles with borders of taenite which merge with the taenite lamellae of the pearlitic structure. Compare the similar structure in San Cristobal (pls. 29, 30). As in the latter iron, with strong etching the kamacite lamellae here shown are clear while the taenite lamellae become gray because of slight supersaturation with respect to kamacite. Picral 20 seconds; × 300.

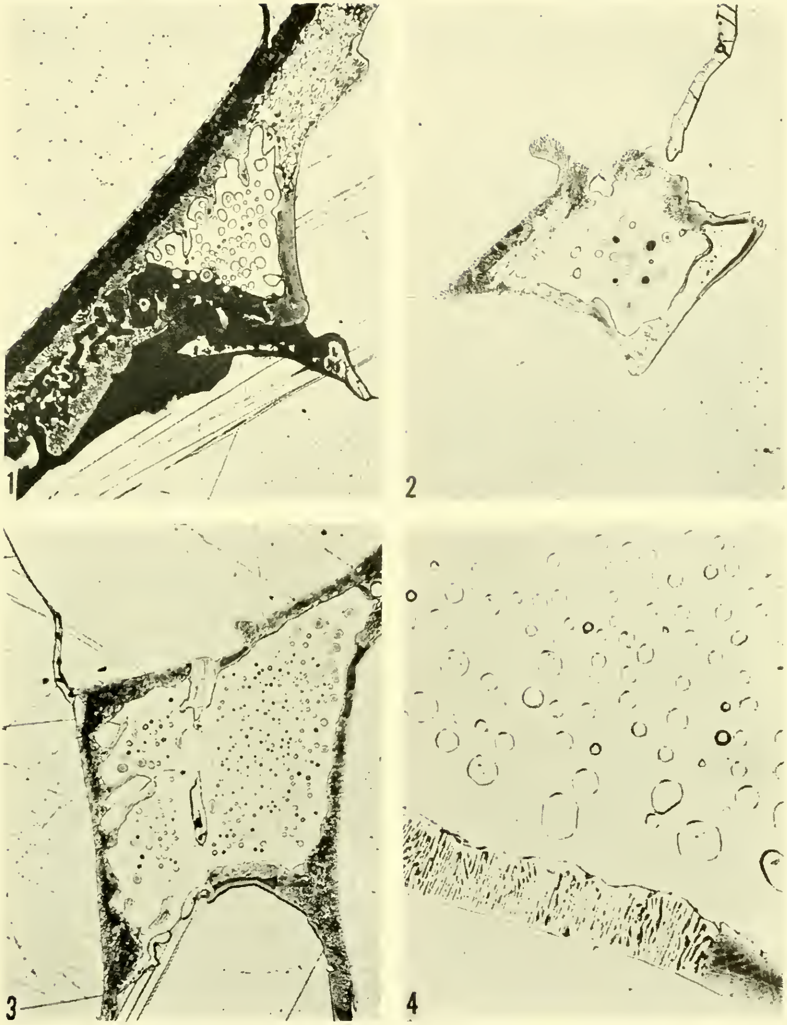
Plate 46

1. Leeds, Quebec; medium octahedrite, no analysis. The specimen, locality unknown, came with other minerals from Leeds and was recognized in 1937. A plessite field showing spheroidized taenite and (lower left) small areas of pearlitic structure. Picral 60 seconds; × 60.

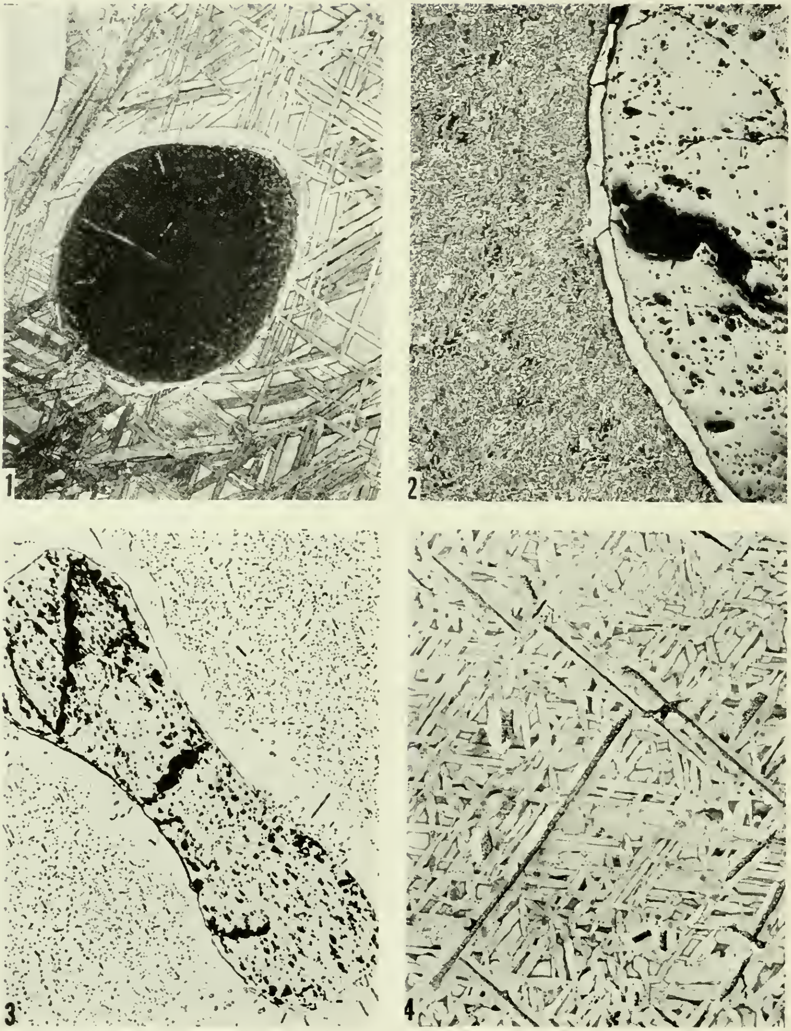
2. Otumpa, Argentina; hexahedrite; Ni-Co 5.68 percent. A plessite field of unusual character, the clear kamacite interior containing spherules of taenite, some of them showing dark cores due to incomplete transformation. The surrounding taenite border is gray in places because of supersaturation. The broadened border at upper left consists of dark plessite with a pearlitic structure. Schreibersite inclusion, upper right. Very similar fields are found in Seeläsgen and Youndegin. Otumpa was classified by Brezina and by Cohen as a nickel-poor ataxite, and is still so listed in museums. It is actually a granular hexahedrite, in many places showing a profusion of Neumann lines, and numerous plessite fields of various structures. (See pl. 44.) Light picral; × 60.

3. Seeläsgen, Prussia; coarsest octahedrite; for composition see plate 38. A plessite field amost indentical with that shown in figure 2. The spherules are smaller and more numerous and the dark plessite with pearlitic pattern more abundant. Small schreibersite bodies in the field and along grain boundaries at upper left. Picral 60 seconds; × 60.

4. Seeläsgen. Part of the area shown in figure 3. In the border the pearlitic plessite abuts against gray taenite. Picral 30 seconds; × 300.



LEEDS, OTUMPA, AND SEELÄSGEN METEORITES.



APOALA, MONAHANS, WALKER COUNTY, AND BREECE METEORITES.

PLATE 47

1. APOALA, Mexico; described by Cohen as a fine octahedrite; no analysis. A typical nodule of troilite surrounded by a band of swathing kamacite. At the upper left are two parallel Reichenbach lamellae about an inch long, their direction unrelated to the general octahedral pattern. Macroetch; × 1⅕, ordinary light.

2. MONAHANS, Texas; nickel-rich ataxite; Ni-Co 11.51 percent. Part of a large troilite inclusion with interface of swathing kamacite. The latter might be mistaken for schreibersite, but etching with neutral sodium picrate proves it to be kamacite. Picral 60 seconds; × 30.

3. WALKER COUNTY, Alabama; hexahedrite; Ni-Co 5.94 percent, P 0.28 percent. An inclusion of troilite surrounded by a zone of clear kamacite, corresponding with the swathing kamacite in octahedrites. The zone is virtually free from the rhabdites and phosphide particles, which are abundant elsewhere, but is traversed by the same Neumann lines as the surrounding mass. Picral; × 60.

4. BREECE, New Mexico; medium octahedrite. An example of Reichenbach lamellae remarkable for their fineness and regularity. (Usually they are thicker, more or less irregular, and less perfectly oriented.) The lamellae running from lower left to upper right happen to be parallel with one set of kamacite bands. Macroetch; × 1⅕, ordinary light.

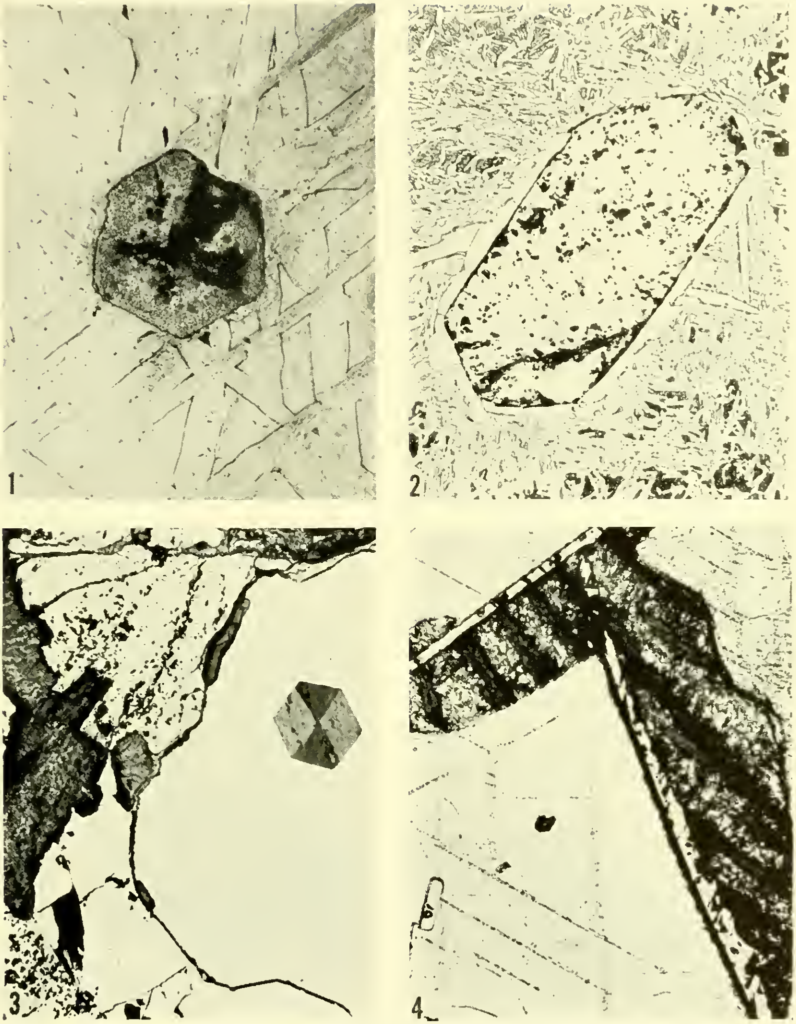
PLATE 48

1. SENECA TOWNSHIP, Michigan; finest octahedrite; Ni-Co 11.67 percent. Hexagonal crystal of troilite about 3 mm. in diameter. Its planes are unrelated to the surrounding octahedral structure. Macroetch; × 9, ordinary light.

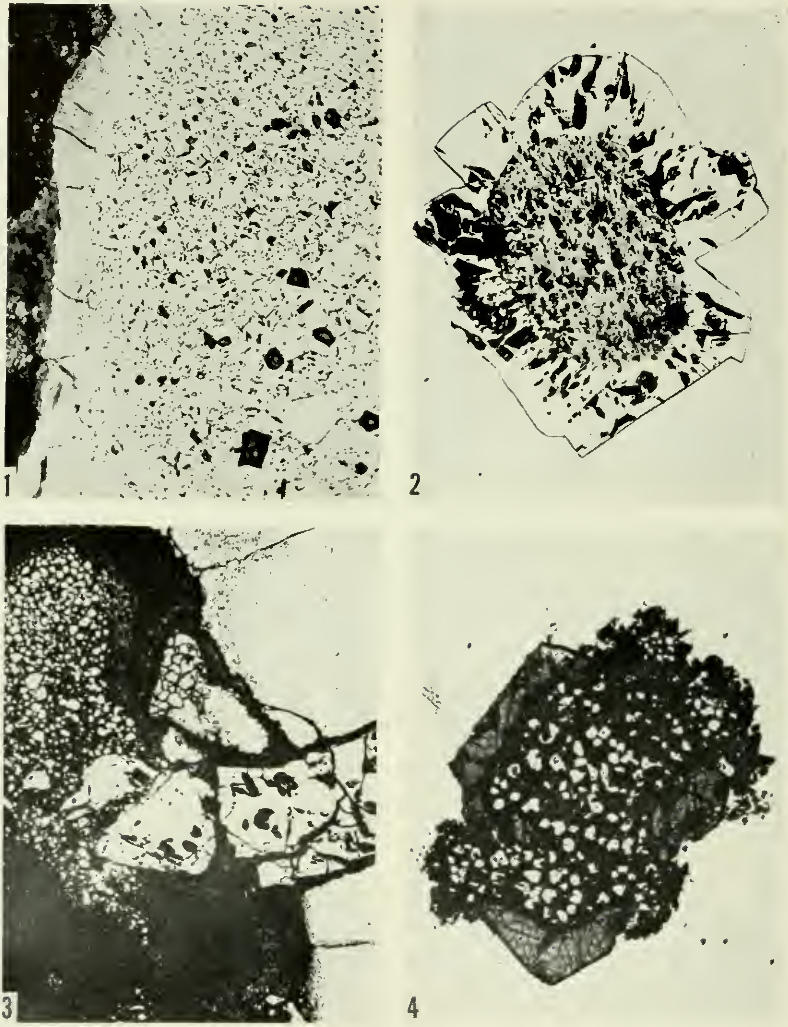
2. MONAHANS, Texas; nickel-rich ataxite; Ni-Co 11.51 percent. Troilite inclusion showing definite hexagonal angles, bordered by an irregular band of swathing kamacite. Picral 40 seconds; × 60.

3. OTUMPA, Argentina; hexahedrite; Ni-Co 5.68 percent. One of several minute highly perfect crystals of troilite observed in this iron. The triangular shadings may be due to variations in the attack of the etchant according to the directions of the crystallographic planes. Light picral; × 60.

4. HEX RIVER MOUNTAINS, South Africa; hexahedrite; Ni-Co 6.34 percent. An inclusion of intergrown troilite and daubréelite, with two schreibersite needles (lamellae). The lighter bands are daubréelite, the darker troilite. The former, more resistant to etching, reflect more light than the latter. The occurrence of these two substances in a banded pattern is not uncommon. Picral; × 60. U. S. National Museum.



SENECA TOWNSHIP, MONAHANS, OTUMPA, AND HEX RIVER MOUNTAINS METEORITES.



Wood's Mountain, Walker County, and Cedartown Meteorites and One Unidentified.

PLATE 49

1. WOOD'S MOUNTAIN, North Carolina; finest octahedrite; Ni-Co 8.61 percent. The nickel content is very low for a finest octahedrite. Part of a large troilite inclusion showing the microstructure of irregular polyhedral grains. The black spots are oxide (visible unetched). A band of swathing kamacite at left side of inclusion. The large dark area is oxide. Picral; × 60.

2. WALKER COUNTY, Alabama; hexahedrite; Ni-Co 5.94 percent. Rounded troilite inclusion surrounded by schreibersite. The black spots are due to chipping. Picral; × 60.

3. UNIDENTIFIED. A medium octahedrite, locality unknown (see pl. 74). A body of troilite is partly penetrated by an elongated schreibersite body. By the reheating of this iron the troilite and part of the schreibersite were fused. The two being almost insoluble with each other in the solid state, the schreibersite in cooling was rejected from the solution in droplike particles. Picral 80 seconds; × 60.

4. CEDARTOWN, Georgia; hexahedrite; Ni-Co 5.70 percent. Troilite inclusion surrounded by schreibersite, etched with sodium picrate only; × 150. The small proportion of phosphide remaining in solution with the troilite is enough to cause the latter to be darkened by picrate. In this case, unlike the preceding, it seems probable that the included white spots are kamacite rejected as the kamacite-sulphide solution cooled. In such cases it usually is rejected to the borders of the inclusion as "swathing kamacite," but in this case that process was inhibited by the presence of the surrounding phosphide which solidified while the inclosed troilite still contained more kamacite than it could retain in solid solution at room temperature.

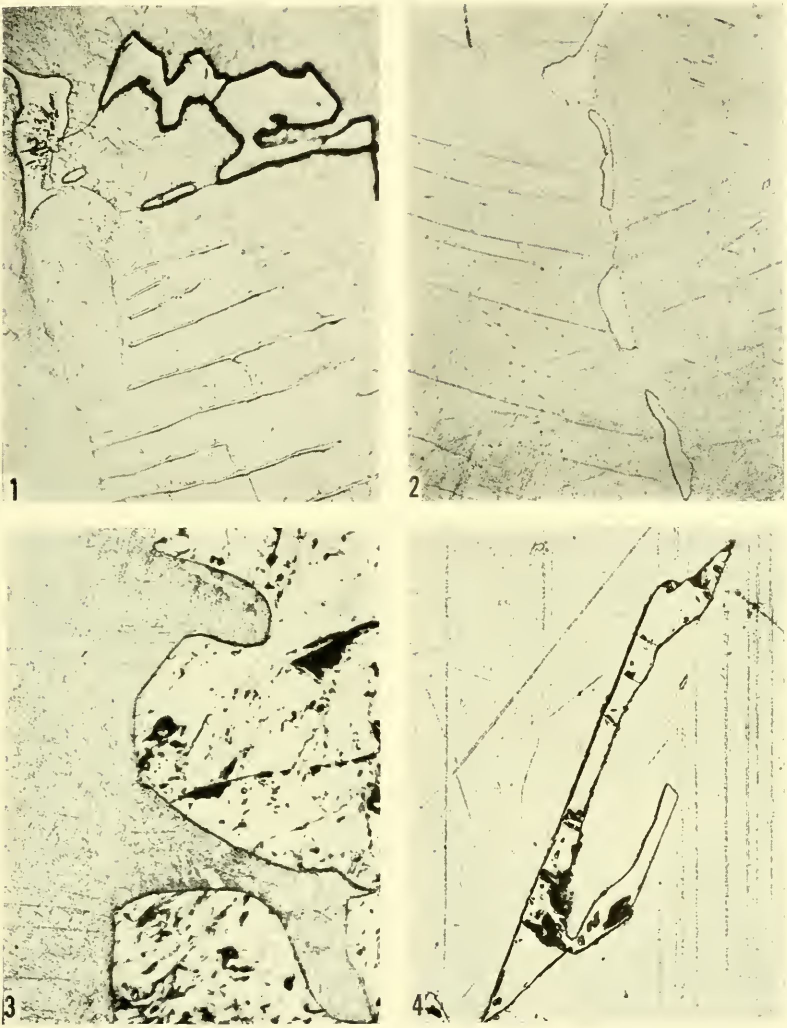
PLATE 50

1. HELT TOWNSHIP, Indiana; coarsest octahedrite; no analysis. Typical irregular inclusion of schreibersite. The darkened border is due in some measure to the effect of strong etching along the interface but is chiefly an optical effect sometimes seen around schreibersite inclusions; the inclusion having been left in relief by polishing, reflects light away from its borders. Upper left, a body of taenite. Below, very coarse plessite field of taenite lamellae. Picral 3 minutes; × 60.

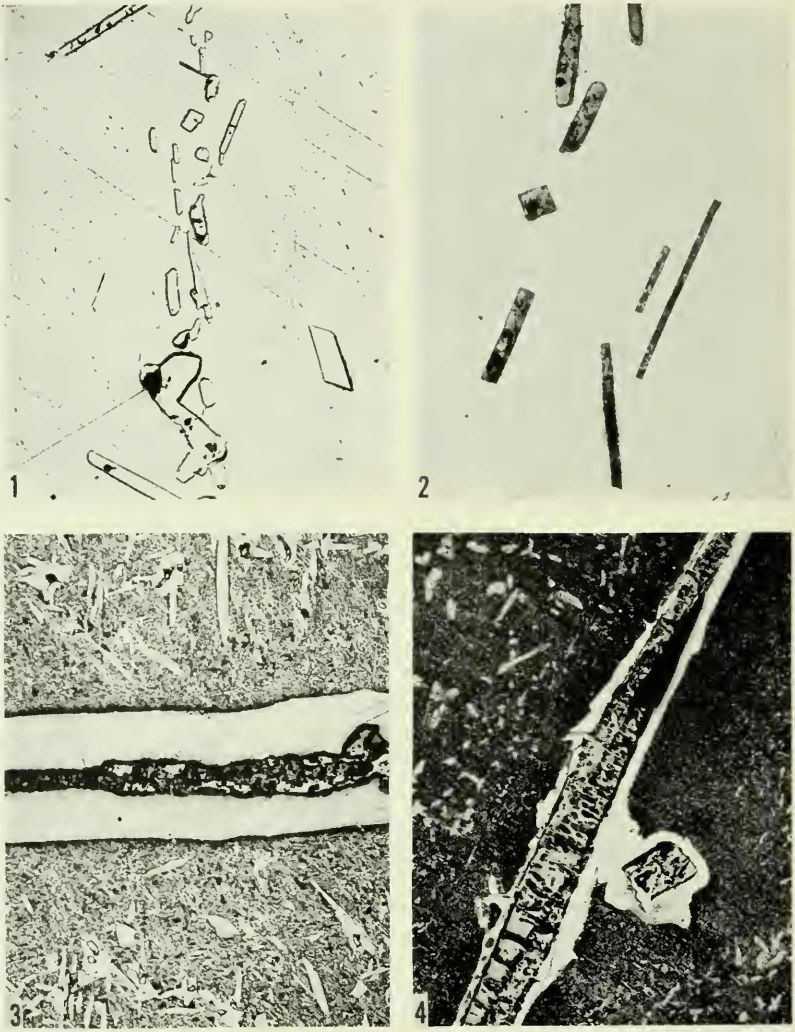
2. HELT TOWNSHIP. Alternating bodies of taenite (darker) and schreibersite (lighter) along a grain boundary. Partial alteration by heating during atmospheric flight has produced a band of incipient granulation along the line of the inclusions in which Neumann lines are obliterated. Picral 2 minutes; × 60.

3. SMITH'S MOUNTAIN, North Carolina; fine octahedrite, Ni-Co 8.52 percent. Part of a large irregular inclusion of schreibersite. The inclusion is bounded in several places by a straight line (parts of it visible at top and bottom of the photograph) which apparently marks a crystallographic plane. The surface was chipped in polishing. Picral 80 seconds; × 30. U. S. National Museum.

4. BRAUNAU, Bohemia; hexahedrite; Ni-Co 6.13 percent. Typical irregular schreibersite body, characteristic of many hexahedrites. Three sets of indistinct Neumann lines. Picral; × 60.



HELT TOWNSHIP, SMITH'S MOUNTAIN, AND BRAUNAU METEORITES.



HEX RIVER MOUNTAINS, CEDARTOWN, WILEY, AND SHINGLE SPRINGS METEORITES.

PLATE 51

1. HEX RIVER MOUNTAINS, South Africa; hexahedrite; Ni-Co 6.34 percent, P 0.23 percent. Part of a band of needles and irregular bodies of schreibersite. Long parallel bands of that character are found in other hexahedrites. Large rhabdite at right. Picral; × 60. U. S. National Museum.

2. CEDARTOWN, Georgia; hexahedrite; Ni-Co 5.70 percent, P 0.30 percent. Part of a long band of inclusions similar to figure 1, but of regular crystalline form. Profuse Neumann lines. Picral and 10 minutes neutral sodium picrate; × 30.

3. WILEY, Colorado; nickel-rich ataxite; Ni-Co 12.31 percent. Part of a long schreibersite inclusion surrounded by kamacite containing Neumann lines. The minute spindles and particles of kamacite, which are profuse in this iron (pl. 19), are absent near the inclusion, all the excess kamacite having been absorbed into the larger body. Another explanation of the absence of kamacite spindles may have been the absorption of phosphide into the schreibersite body, resulting in the absence of small phosphide particles, which elsewhere are found inside the kamacite spindles and which might have served as nuclei for the precipitation of kamacite. Picral 50 seconds; × 30.

4. SHINGLE SPRINGS, California; nickel-rich ataxite; Ni-Co 17.34 percent, P 0.34 percent. A structure similar to the preceding. The schreibersite needle and the smaller schreibersite body are surrounded by kamacite. Like Wiley, this iron in general shows a profusion of minute kamacite bodies, but they are sparse or absent near such inclusions. Picral 70 seconds; × 30. U. S. National Museum.

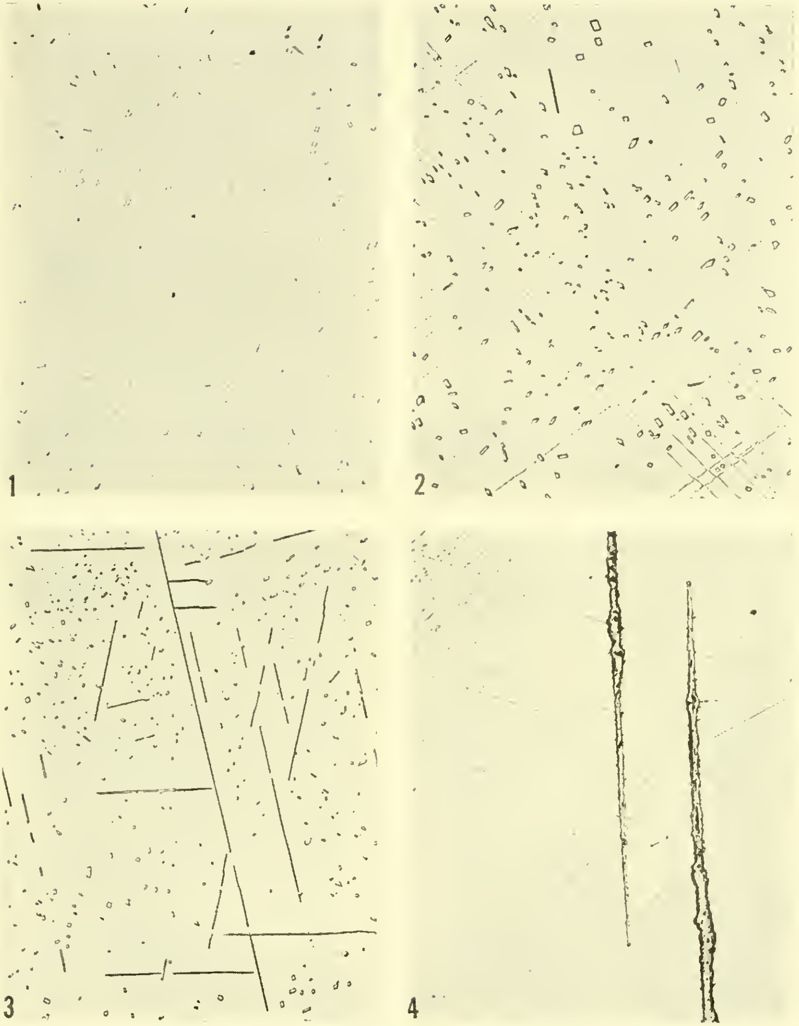
PLATE 52

1. WALKER COUNTY, Alabama; hexahedrite; Ni-Co 5.94 percent, P 0.28 percent. Rhabdites, unetched—an example of so-called "relief etching." Many hexahedrites show a profusion of such rhabdites.

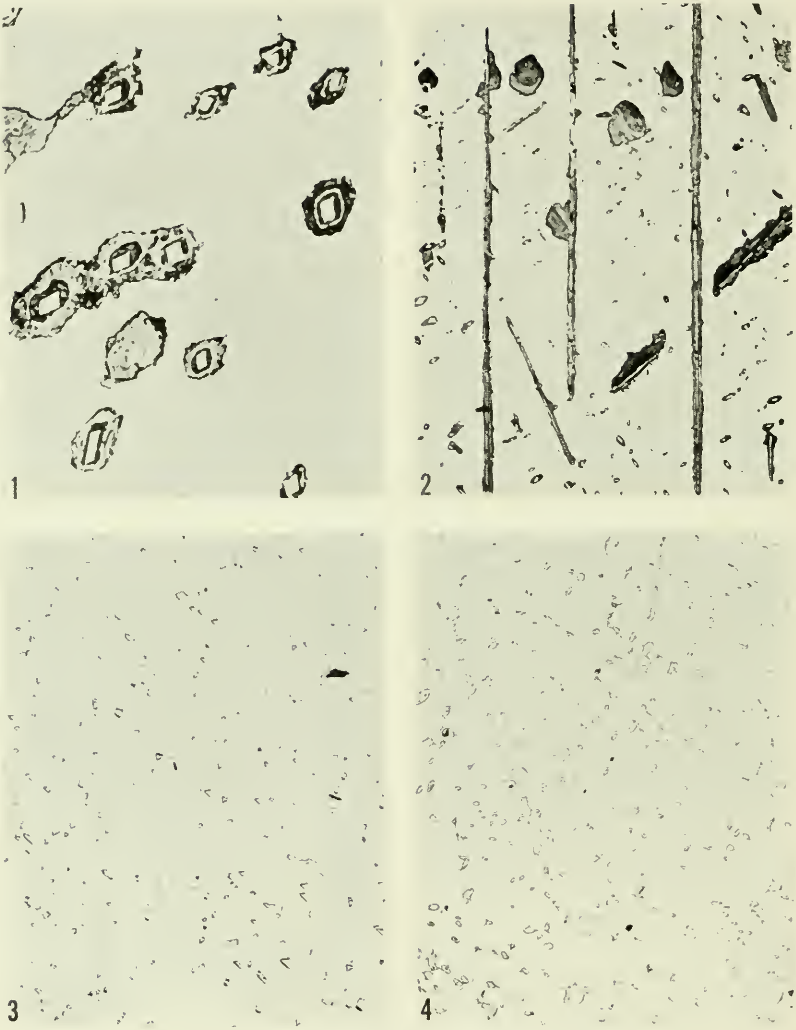
2. WALKER COUNTY. An area similar to figure 3, etched. Neumann lines are revealed, and the rhabdites have sharp black outlines due to the strong attack of the etchant on interfaces. Picral; × 60.

3. WALKER COUNTY. Exceedingly fine and long schreibersite needles (lamellae), oriented in three directions. Their orientation is different from that of the Neumann lines, one set of which is faintly distinguishable. One lamella (upper right) is broken and slightly displaced where it crosses the planes of two Neumann lines. Rhabdites and fine phosphide particles. Picral; × 60.

4. SIERRA GORDA, Chile; hexahedrite; Ni-Co 5.83 percent. Parallel, thick needles of schreibersite. Four sets of Neumann lines can be distinguished. Picral 200 seconds; × 60.



WALKER COUNTY AND SIERRA GORDA METEORITES.



Walker County and Río Loa Meteorites.

PLATE 53

1. WALKER COUNTY, Alabama; hexahedrite; Ni-Co 5.94 percent, P 0.28 percent. Rhabdites surrounded by oxide. One rhabdite is free from oxide. That the dark aureoles are oxide, and not diffused phosphide (as in some cases), is indicated by the sharp unaltered angles of the crystals. It is definitely proved by the fact that they are visible on an unetched surface. Picral 40 seconds; × 600.

2. WALKER COUNTY. An area showing rhabdites and phosphide particles surrounded by oxide, and also long fine needles (like those in pl. 52, fig. 3) bordered by oxide. Unetched; × 60. Field Museum of Natural History.

3. Río LOA, Chile; hexahedrite, Ni-Co 5.70 percent. General structure of the iron, normal rhabdites and Neumann lines. This iron etches slowly. Picral 150 seconds; × 60.

4. Río LOA. An area in the zone of alteration near edge of slice, where the structure has been changed by superficial heating during atmospheric flight. Neumann lines are obliterated and rhabdites have been changed by fusion into shapeless particles. Picral 150 seconds; × 60.

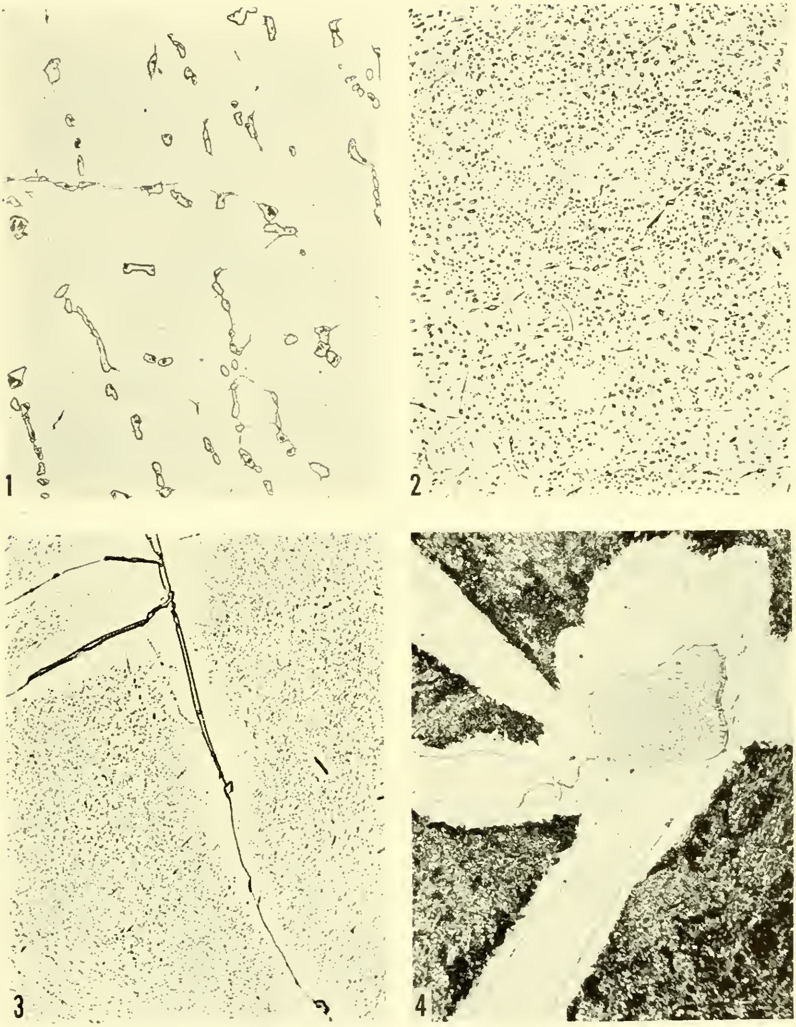
PLATE 54

1. ZACATECAS, Mexico. Classified as a brecciated octahedrite, although the specimen studied shows no octahedral structure. The most satisfactory analysis, given by Cohen (Cohen and Weinschenk, Meteoreisen-Studien, vol. 5, p. 51, 1897) gives Ni 5.98 percent, Co 0.91 percent, P 1.02 percent. Copious segregations of phosphide along grain boundaries; compare Soper, pl. 11). Picral 75 seconds; × 30.

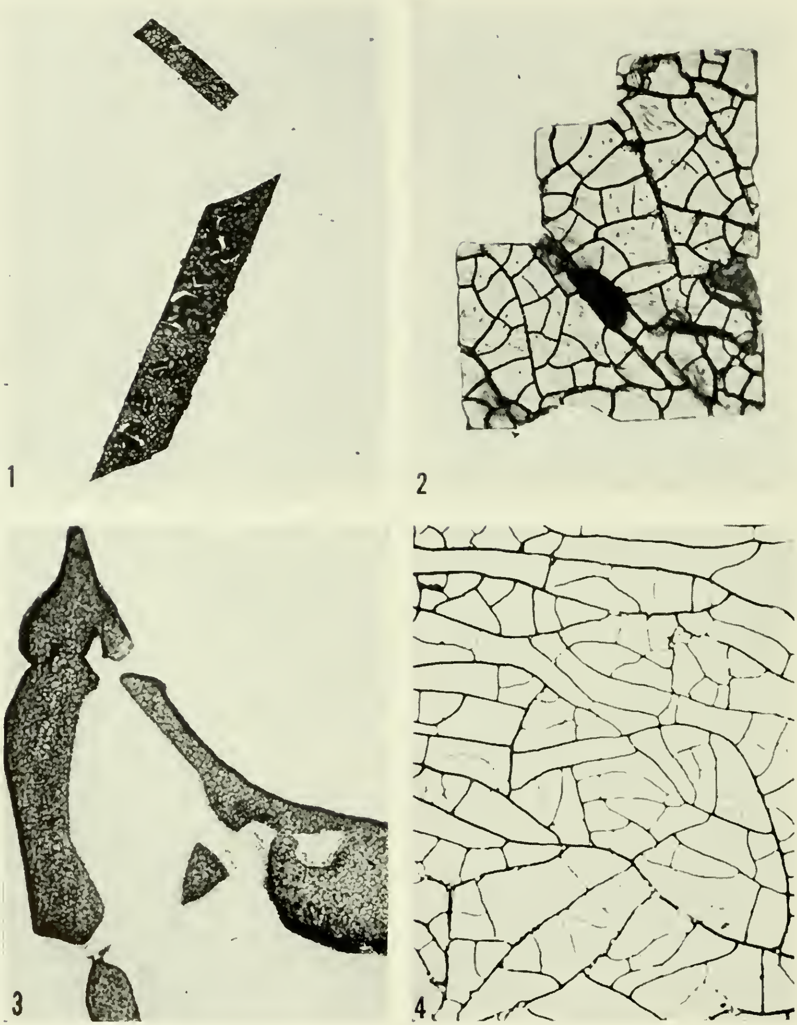
2. ZACATECAS. In other parts of this iron, as here shown, the phosphide appears as a thick dispersion of minute particles. Picral 50 seconds; × 60.

3. WICHITA COUNTY, Texas; coarse octahedrite; Ni 7.93 percent, Co 0.40 percent (Cohen, in Cohen and Weinschenk, 1891). The phosphorus content is not available, though it obviously is considerable. The fine dispersed particles are absent in the vicinity of the schreibersite bodies. Picral 35 seconds; × 60.

4. COWRA, Australia; ataxite or finest octahedrite; Ni-Co 14.25 percent. The abundant kamacite spindles (pl. 17) contain many inclusions of schreibersite. An example of such an inclusion in an area near the surface of the mass, which shows a characteristic iron-phosphide eutectic structure. Picral 30 seconds; × 150.



ZACATECAS, WICHITA COUNTY, AND COWRA METEORITES.



Cedartown, Helt Township, and Kendall County Meteorites.

PLATE 55

1. CEDARTOWN, Georgia; hexahedrite; Ni-Co 5.70 percent, P 0.30 percent. Schreibersite needles showing apparently an iron-phosphide eutectic structure. That seems more clearly true of the larger needle; the appearance of the smaller one suggests a stain pattern. Such a structure in this case would probably be primary, forming as the mass cooled, and not a product of reheating. The light etching with picrate alone reveals no structure in the kamacite groundmass. Neutral sodium picrate 5 minutes; × 150.

2. CEDARTOWN. An angular schreibersite body with a reticulated stain pattern. The same etching as the preceding; × 600.

3. HELT TOWNSHIP, Indiana; coarsest octahedrite; no analysis. A schreibersite inclusion with a eutectic structure which is refined and uniform. It apparently originated in the gamma phase, slow transformation permitting an orderly absorption of the excess of iron from the iron-phosphide solution into the surrounding mass with no droplets of iron rejected. The etching reveals no structure in the kamacite. Light neutral sodium picrate; × 150.

4. KENDALL COUNTY, Texas; granular hexahedrite; Ni-Co 6.42 percent, P 0.34 percent. Part of an inclusion of schreibersite showing a reticulated stain pattern. Light picral and neutral sodium picrate; × 600.

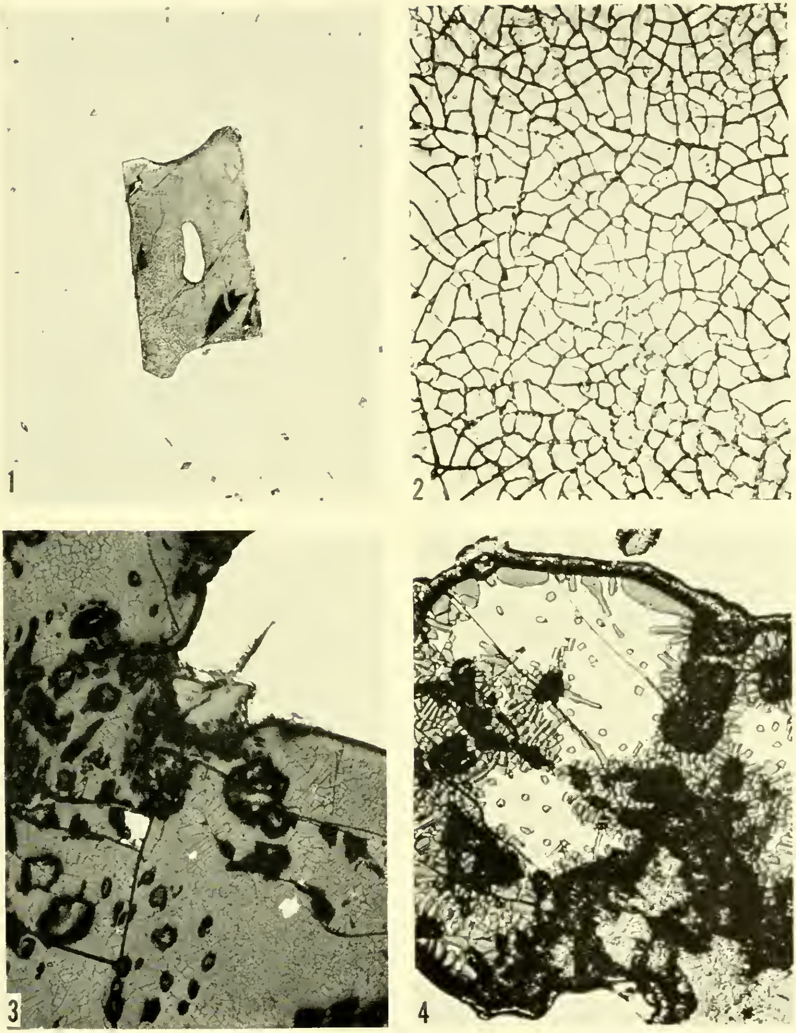
PLATE 56

1. **FORT DUNCAN**, Texas; hexahedrite; Ni-Co 5.89 percent, P 0.23 percent. A rhomboidal schreibersite body with a spot of kamacite in the center, a form occasionally observed in hexahedrites. Rhabdites, abundant elsewhere, are absent near the inclusion. The picrate stain produces a reticulated appearance. Light picral and 5 minutes neutral sodium picrate; × 60. U. S. National Museum.

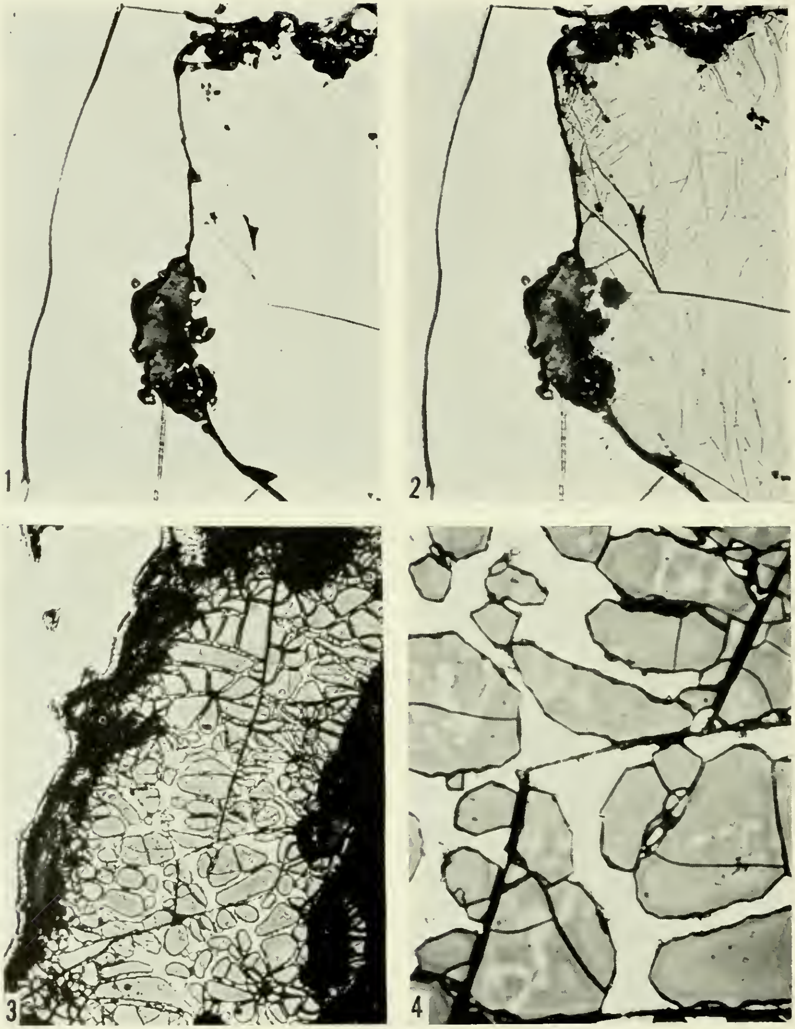
2. **FORT DUNCAN**. Part of the area shown in figure 1, × 600.

3. **PINE RIVER**, Wisconsin; an undescribed iron that may be provisionally classified as an atypical coarsest octahedrite with accessory silicates. Area of kamacite containing phosphide the picrate stain has formed a reticulated pattern. The pellicle of stain is easily dislodged, the touch of a needle point having broken away small portions producing white spots. The black areas are silicate. Light picral and 5 minutes neutral sodium picrate; × 120.

4. **PINE RIVER**. Part of an area similar to figure 3. Light picral and 5 minutes neutral sodium picrate; × 150.



FORT DUNCAN AND PINE RIVER METEORITES.



Pine River Meteorite.

PLATE 57

1. PINE RIVER, Wisconsin; an undescribed iron that may be provisionally classified as an atypical coarsest octahedrite with accessory silicates. An example of a solid solution of phosphorus in nickel-iron; in artificial irons such a homogeneous solid solution should not contain more than about 1.7 percent of phosphorus. With ordinary etching the entire field appears to be kamacite, with dark areas of silicate and oxide. Light picral; × 60.

2. PINE RIVER. The area shown in figure 1 with additional etching 5 minutes with neutral sodium picrate. The area at the right is shown to contain phosphorus, evidently in small proportion as it darkens only slightly and the reticulated pattern of the stain is coarse and faint. Grain boundaries within the phosphorus area appear more distinctly.

3. PINE RIVER. An example of a coarse reticulated pattern in the pellicle of picrate stain. Light picral and 5 minutes neutral sodium picrate; × 150.

4. PINE RIVER. Part of the area shown in figure 3, × 600. Portions of grain boundaries are apparently darkened by hydroxide.

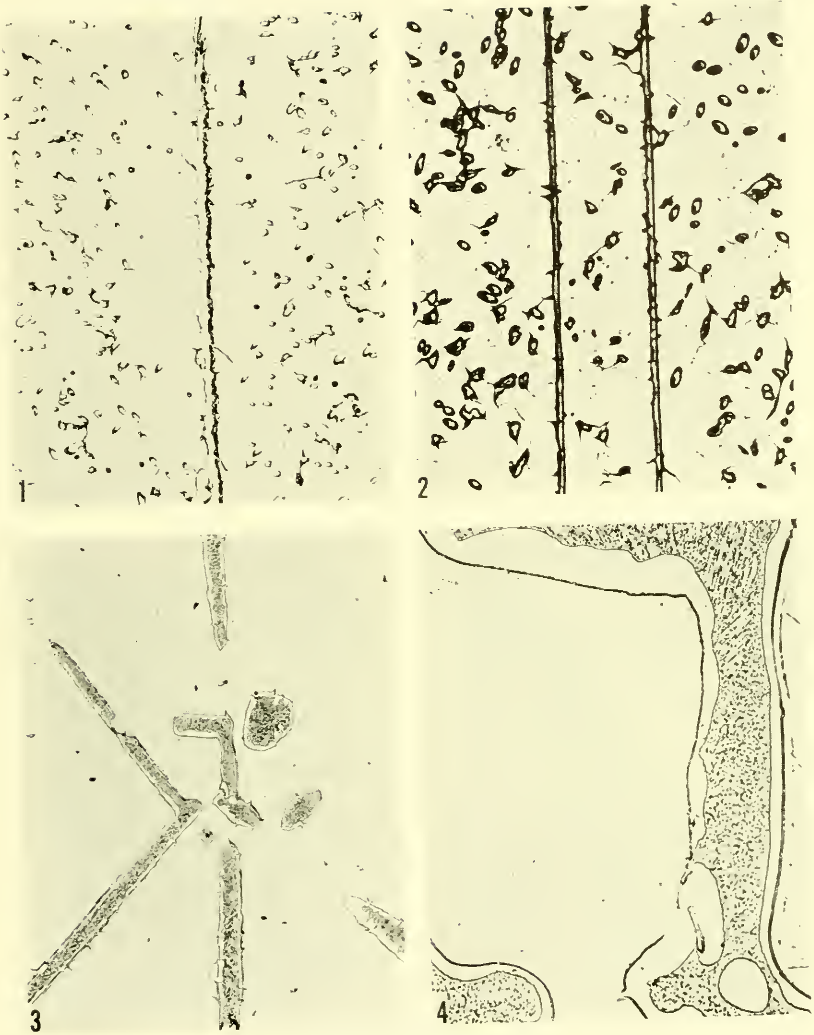
PLATE 58

1. Río LOA, Chile; hexahedrite; Ni-Co 5.70 percent. Typical area in zone of alteration, with a profusion of rhabdites and part of a long schreibersite needle (lamella). Rhabdite crystals have lost their form and become rounded by fusion. The needle, and many of the rhabdites, show thornlike projections, caused by diffusion of the melted phosphide along grain boundaries. Picral 200 seconds; × 60.

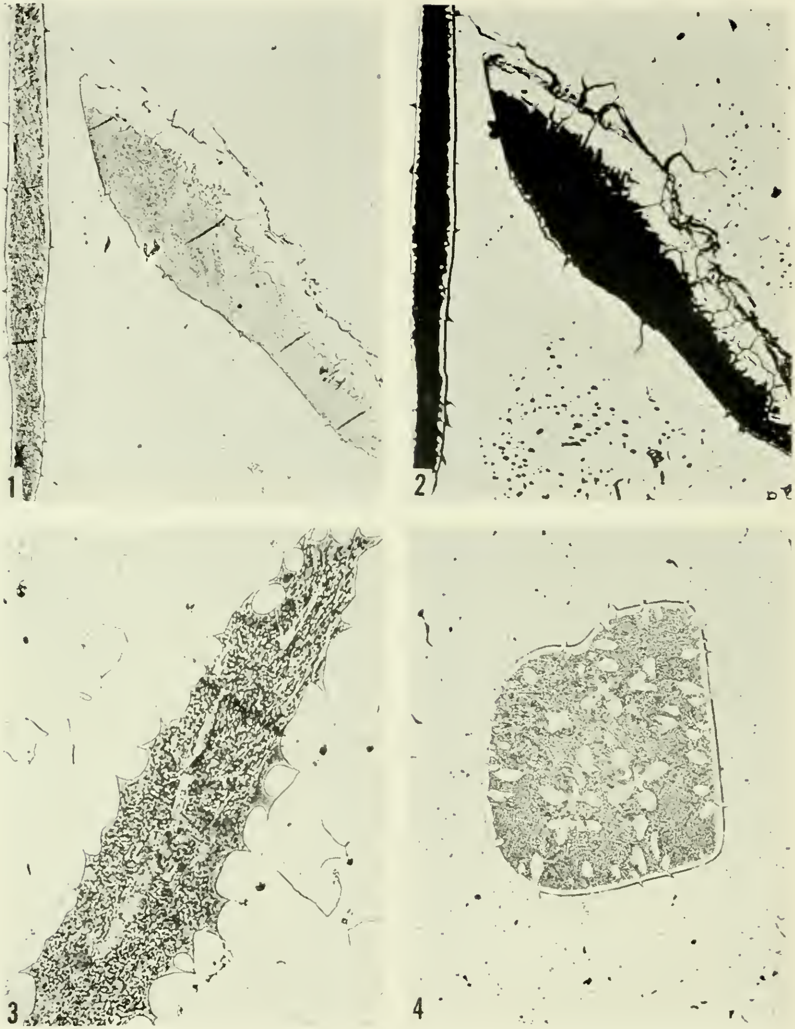
2. Río LOA. An area similar to figure 1 showing two parallel needles. Picrate etching blackens the phosphide and makes more conspicuous its invasion of the surrounding nickel-iron along grain boundaries. The faint incipient granulation, not visible in figure 1, is the result of superficial heating during atmospheric flight. The fact that it is brought out by picrate etching suggests a trace of phosphide enrichment along the grain boundaries. Picral 200 seconds and 5 minutes neutral sodium picrate.

3. Río LOA. A group of schreibersite needles in the zone of alteration. The brief heating fused the phosphide and obliterated the Neumann lines. The liquid phosphide of the needles absorbed iron from the surrounding mass, and as it cooled the excess of iron above the eutectic ratio was rejected. The eutectic core finally solidified, leaving borders and rounded droplets of clear rejected iron. Picral 150 seconds; × 60.

4. Río LOA. Part of the area shown in figure 3 at higher magnification. The eutectic structure of the core is apparent. Picral 150 seconds; × 300.



Río Loa Meteorite.



Río Loa, Chesterville, and Cincinnati Meteorites.

PLATE 59

1. Río LOA, Chile; hexahedrite; Ni-Co 5.71 percent. A needle and a large irregular inclusion of schreibersite, showing remnant of phosphide-iron eutectic. In the needle the phosphide-iron solution contracted to a central position; in the larger body it withdrew to one side. Picral 150 seconds; × 60.

2. Río LOA. The same area as figure 1, with additional 5 minutes neutral sodium picrate. The extensions of the phosphide-iron solution along grain boundaries were entrapped there on cooling and remain isolated. The iron immediately surrounding the inclusions, as usual in such cases, is phosphide-poor, shown by the absence of rhabdites and phosphide particles.

3. CHESTERVILLE, South Carolina; nickel-poor ataxite; Ni-Co 6.25 percent, P 0.34 percent. Inclusion of schreibersite changed by heating to an iron-phosphide eutectic. The entire iron underwent substantially the same change by heating as appears in the zone of alteration in Río Loa, which has a similar composition. The inclusion is almost uniformly eutectic in composition, only a few droplets of kamacite having been rejected during cooling. The fluid eutectic invaded grain boundaries. Picral 40 seconds; × 150. U. S. National Museum.

4. CINCINNATI, Ohio; nickel-poor ataxite; Ni-Co 6.11 percent. An area of iron-phosphide eutectic, similar in origin to the preceding. The eutectic structure is of unusual fineness and regularity, and a considerable proportion of excess iron was rejected in cooling along the interface and in droplike forms. The refinement of the structure indicates comparatively slow cooling. Picral 60 seconds; × 60. American Museum of Natural History.

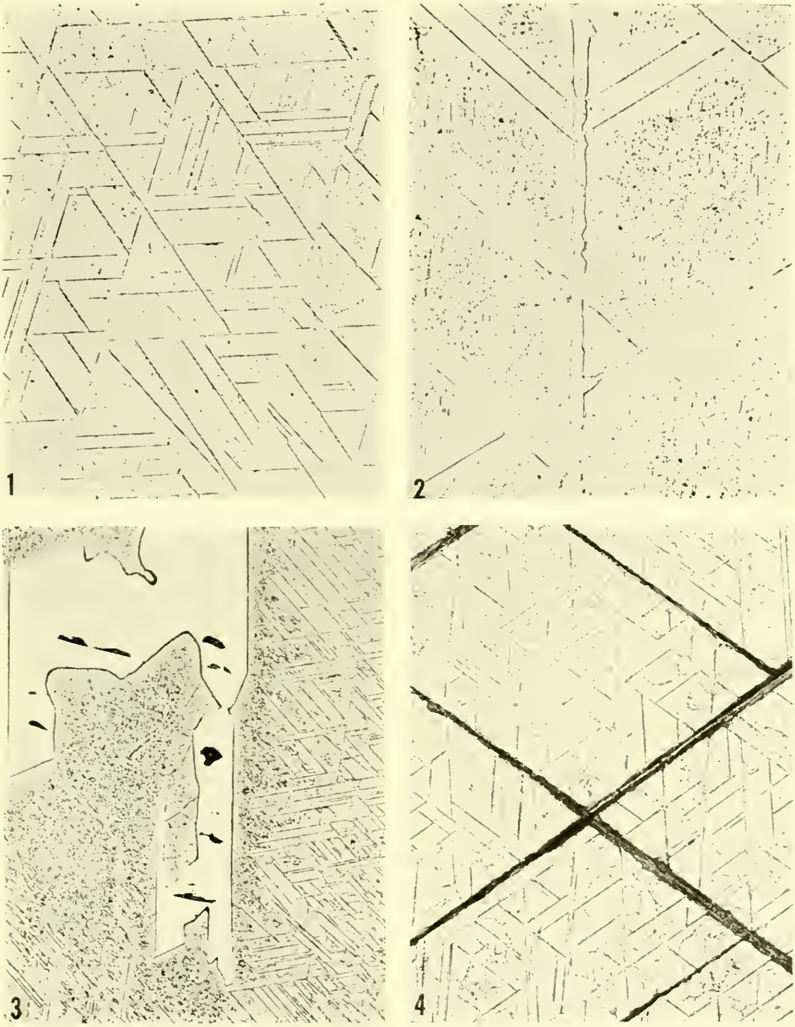
PLATE 60

1. HORSE CREEK, Colorado; an anomalous meteoric iron found in 1937, its original weight 570 grams; no analysis. It consists wholly of kamacite and schreibersite, the latter being abundantly precipitated on the crystallographic planes of the phosphide. As explained on page 64, those planes are not octahedral, although they have that appearance to the eye. Owing to the brittleness of the phosphide the mass breaks easily with a highly perfect cleavage along the planes of the phosphide lamellae. In this specimen the section was made on a plane that gives a pattern of triangles, resembling an octahedrite cut on an octahedral plane. The structure in general is very regular, but in figures 1 and 4 deviations from an octahedral pattern are apparent. Microscopic examination reveals in places as many as six or seven planes of precipitation of the phosphide. Picral 70 seconds; × 60. U. S. National Museum.

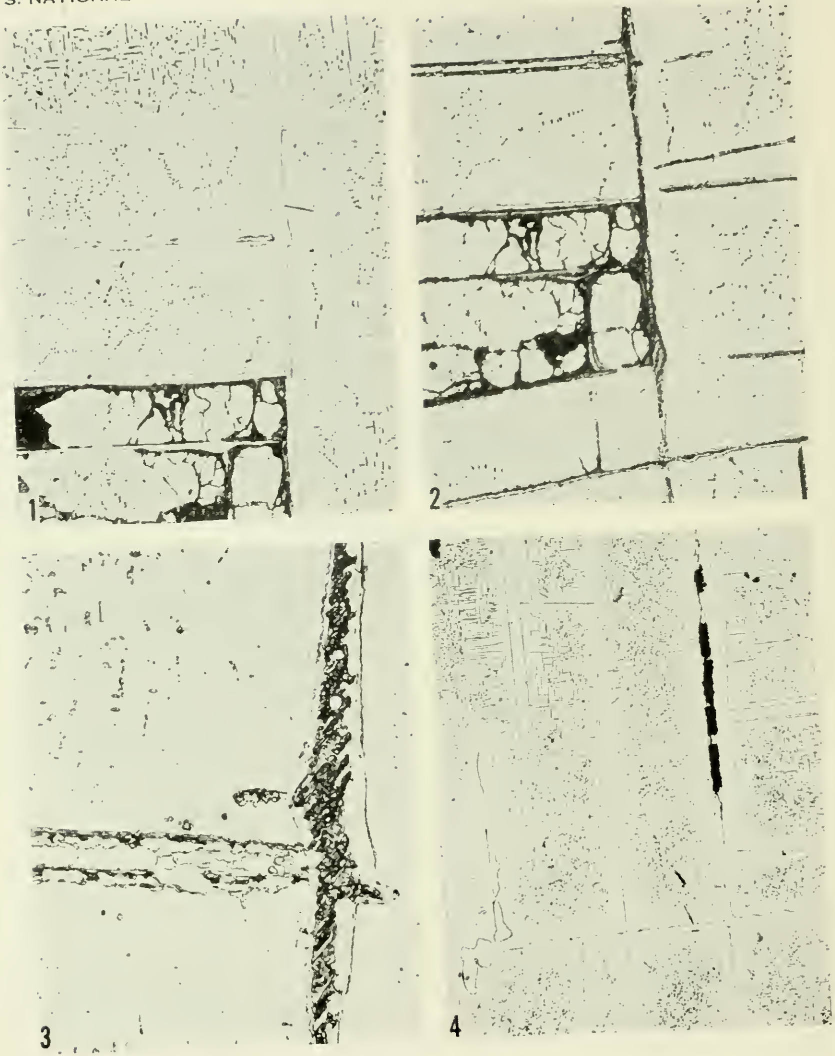
2. HORSE CREEK. Occasionally there are coarser lamellae than appear in figure 1, of which this is an example. Its substance extends into some of the finer lamellae. The very regular fields are filled with minute phosphide particles, which are less plentiful near the lamellae. Picral 40 seconds; × 150.

3. HORSE CREEK. A large schreibersite inclusion with crystallographic planes. In its immediate vicinity the structure is modified, phosphide lamellae giving place to fine particles. Picral 120 seconds; × 30.

4. HORSE CREEK. Hydroxide invading the structure. The oxide penetrates the mass extensively in this manner, adding to its brittleness and ready cleavage. Strong etching here brings out granulation in the kamacite. Picral 120 seconds; × 30.



Horse Creek Meteorite.



Horse Creek Meteorite.

Plate 61

1. Horse Creek. This specimen, unlike that shown in plate 60, was cut along a plane on which the phosphide lamellae make a rectangular pattern. The photograph shows only coarse lamellae, with fine phosphide particles, in some places oriented parallel with the lamellae. One area has been invaded by oxide. Picral 30 seconds; × 150.

2. Horse Creek, The area shown in figure 1, after additional light etching with sodium picrate, darkening the phosphide lamellae. The areas in the two figures are not quite identical, the double horizontal lamella near the center of figure 1 appearing in figure 2 about an inch higher (upper left corner).

3. Horse Creek. Part of the area in figures 1 and 2, showing the double horizontal lamella and the large vertical one. The latter has a phosphide-iron eutectic core, similar to those in Chesterville and Río Loa (pls. 58, 59), but more irregular. Picral 15 seconds and light sodium picrate; × 600.

4. Horse Creek. An area with very fine and also coarser lamellae. The rectangular pattern is reproduced in miniature in some of the areas by extremely fine oriented lamellae. Picral 50 seconds; × 60.

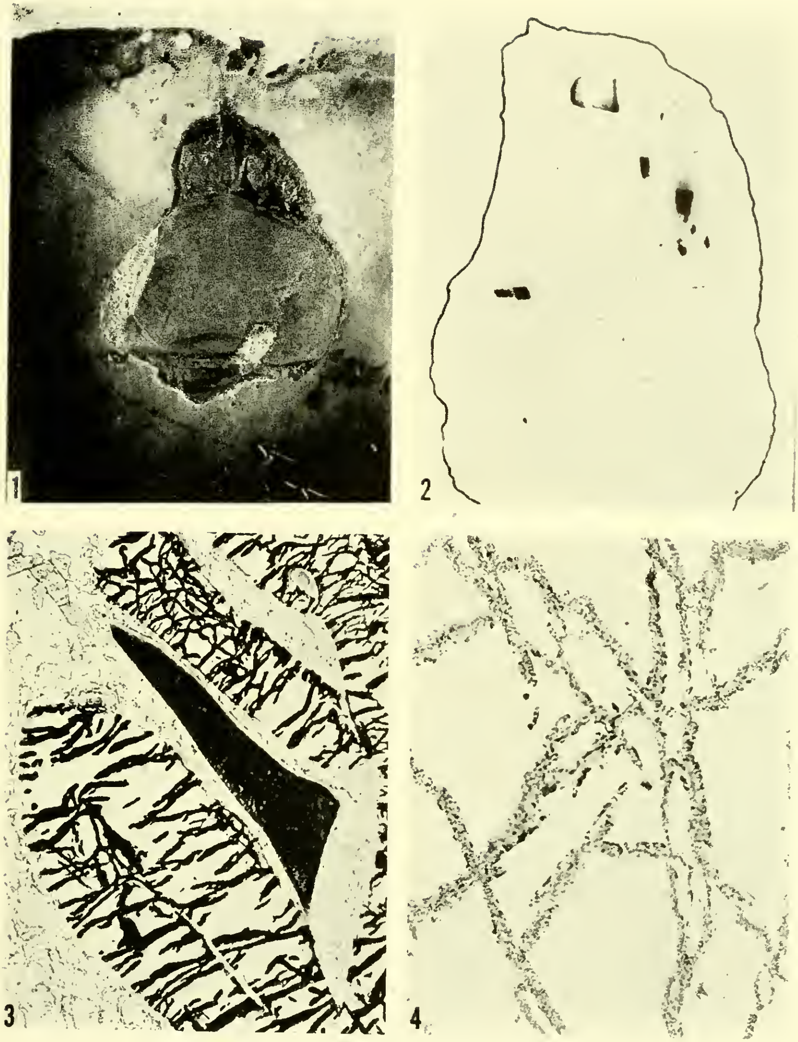
PLATE 62

1. CEDARTOWN, Georgia; hexahedrite; Ni-Co 5.70 percent. Graphite surrounding, and in one place penetrating, a troilite nodule. Unetched; × 6.

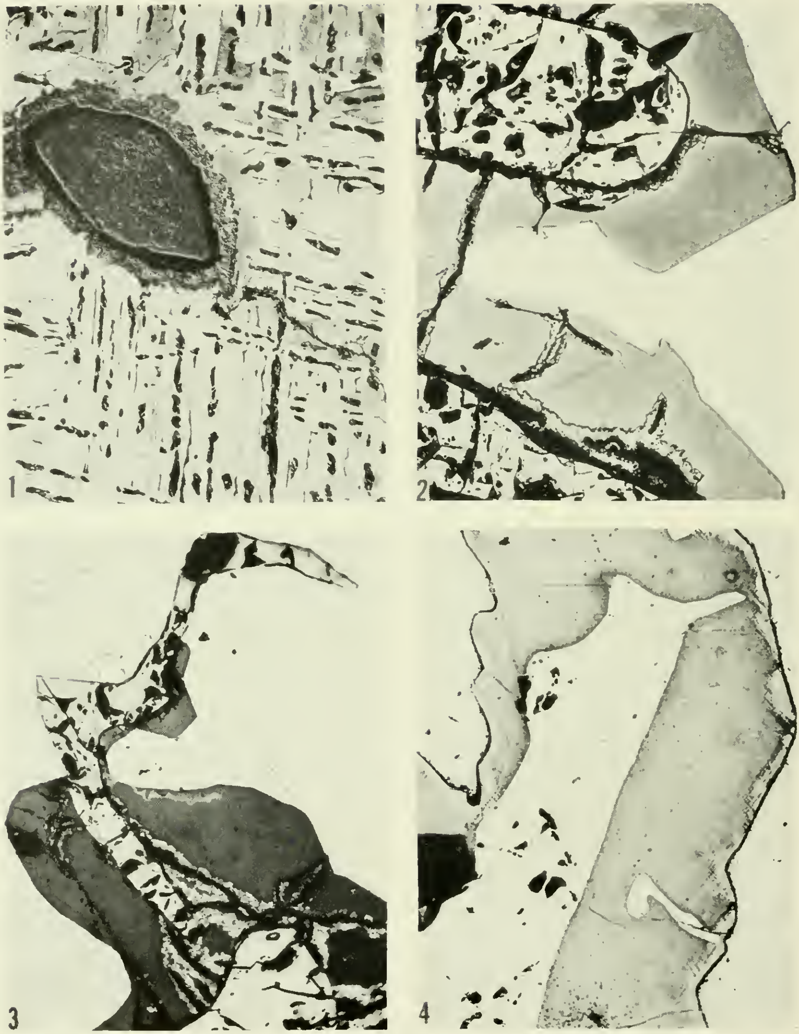
2. CEDARTOWN. A sulphur print showing a number of troilite inclusions. The nodule shown in figure 1 is at top of print. The outline of the troilite body is shown, though not the central part of it; the graphite does not appear in the print.

3. DUNGANNON, Virginia; medium octahedrite altered by reheating; Ni-Co 7.445 percent, P 0.252 percent, C 0.532 percent. The unusually large carbon content appears in arborescent form, as shown in the photograph. Kamacite shows secondary granulation and the plessite, with higher magnification, shows diffusion. Picral 70 seconds; × 30.

4. DUNGANNON. Part of the area shown in figure 3. Unetched; × 300.



Cedartown and Dungannon Meteorites.



WICHITA COUNTY AND CANYON DIABLO METEORITES.

PLATE 63

1. WICHITA COUNTY, Texas; coarse octahedrite. Cohenite is very abundant in this iron, the photograph showing its characteristic form of occurrence as elongated inclusions within the kamacite bands. The troilite inclusion is surrounded by graphite, schreibersite, and some swathing kamacite. Macroetch; × $1\frac{1}{5}$, ordinary light.

The analyses of Wichita County are not satisfactory. Cohen and Weinschenk (Meteoreisen-Studien vol. 6, 1891) reported Ni 7.93 percent, Co 0.40 percent, with no carbon or phosphorus, the sample analyzed evidently having been free from inclusions. Analyses by Manteuffel cited by Cohen (Ibid. vol. 7, 1892) gave Ni 6.74 percent, Co 0.59 percent, and P 0.03 percent; while another analysis gave calculated proportions for the whole mass as Ni 8.62 percent, Co 0.72 percent, P 0.97 percent, and C 0.31 percent. The last nickel percentage seems too high. A fair estimate for the mass would be Ni about 7 percent, Co about 0.50 percent, a substantial phosphorus content, and a relatively high percentage of carbon.

2. WICHITA COUNTY. Cohenite enclosing schreibersite, the latter showing black spots due to surface chipping. Boiling alkaline sodium picrate 1 minute; × 60.

3. WICHITA COUNTY. Irregular schreibersite body intergrown with cohenite. Picral 10 seconds and electrolytic alkaline sodium picrate; × 60.

4. CANYON DIABLO, Arizona; coarsest octahedrite; for analyses see plate 64. Murikami's reagent boiling, 10 minutes; × 60. The cohenite is not further darkened appreciably by longer immersion; it is slightly darkened with 5 minutes' application. With this reagent scratches are brought out conspicuously. Although this sample was polished with an exceedingly fine magnesium oxide, used for metallographic polishing of soft metals, the scratches could not be eliminated.

PLATE 64

1. CANYON DIABLO, Arizona; coarsest octahedrite. Portions of four areas of cohenite (white) surrounded by kamacite, with an irregular taenite lamella (V-shaped, lower right). The dark area is plessite. The cohenite is indistinguishable from schreibersite. Picral 80 seconds; × 30.

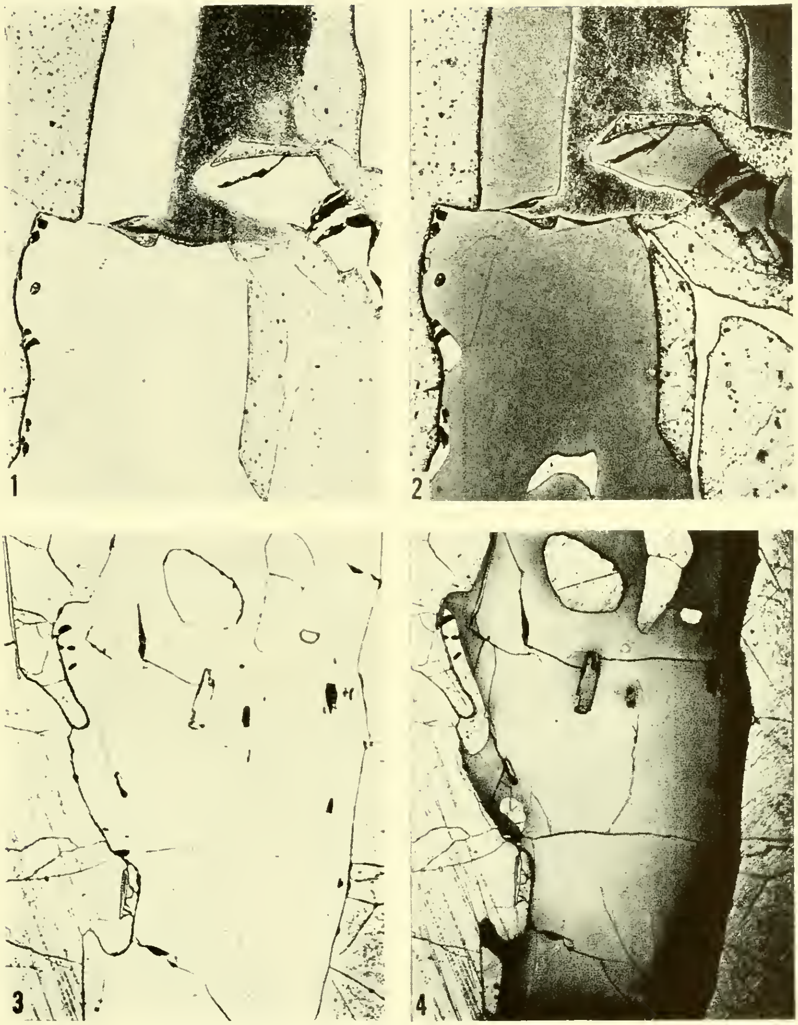
2. CANYON DIABLO. The area shown in figure 1 with additional 10 seconds electrolytic etching with alkaline sodium picrate, darkening the cohenite. Two small schreibersite bodies (uncolored) are revealed at the left edge of the larger cohenite area. The V-shaped lamella is shown to be taenite.

Owing to diversities of structure in different masses, and even in parts of the same mass, analyses of Canyon Diablo vary widely. Thus Moissan (1893) found in different parts of the same sample 3.07 percent and 5.07 percent of nickel, while Booth, Garrett, and Blair (in Barringer, 1905) found 7.94 percent. The latter analysts found the large proportion of 0.417 percent of carbon, though Moissan reported none. Moissan found 0.20 percent phosphorus in one sample, in another none. Carbon actually occurs abundantly, both in occasional nodules of graphite and in combined form as cohenite, the latter profuse in some samples and absent in others.

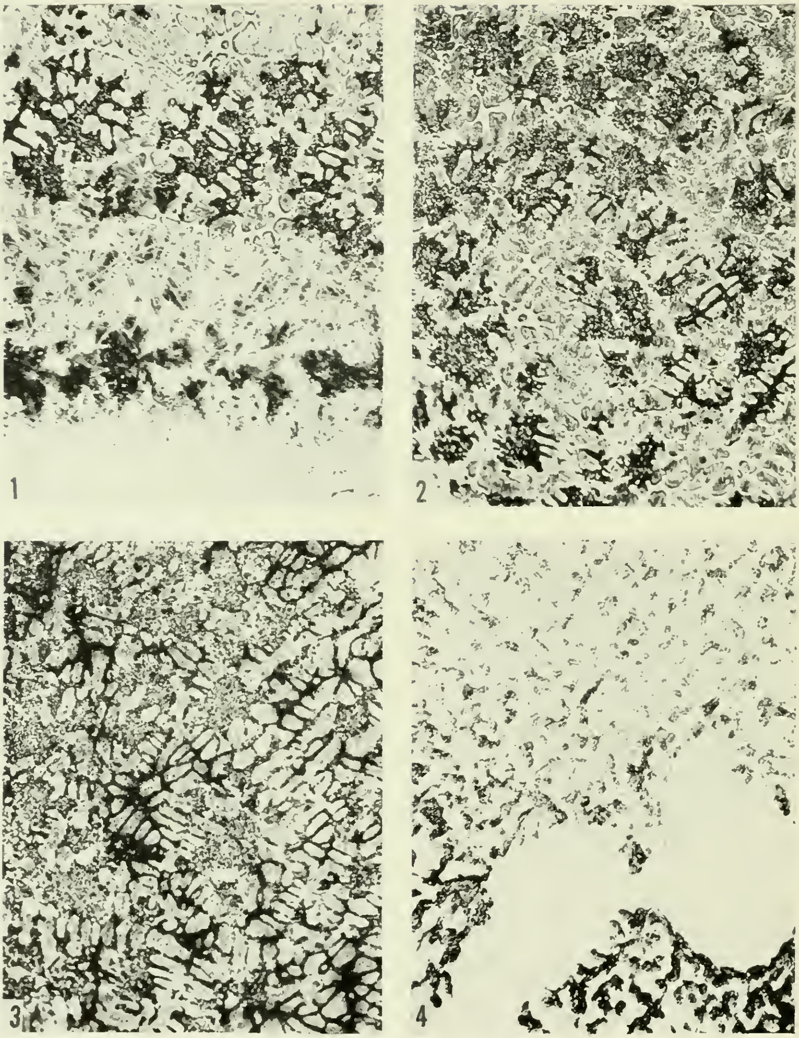
3. COSBY CREEK, Tennessee; coarse octahedrite; Ni-Co 7.42 percent. A large area of cohenite enclosing several small inclusions the nature of which is not apparent, surrounded by coarsely granular kamacite. Picral 60 seconds; × 30.

4. COSBY CREEK. The same area as figure 3 with additional 10 seconds electrolytic etching with alkaline sodium picrate. The small inclusions, along the left side of the cohenite area, are shown to be schreibersite. The rounded islands are kamacite, identical with the groundmass.

Several analyses of Cosby Creek have been made, of which the latest by Fahrenhorst (in Cohen, 1900) gives Ni 6.91 percent, Co 0.51 percent, P 0.37 percent. Cohenite apparently is not mentioned in the literature of this iron, nor does carbon appear in any of the analyses except the first made by Troost in 1840, who reported 0.50 percent.



Canyon Diablo and Cosby Creek Meteorites.



Locust Grove Meteorite.

PLATE 65

1. LOCUST GROVE, Georgia; nickel-poor ataxite; Ni-Co 6.21 percent, P 0.18 percent, C 0.02 percent. Interface of a large inclusion showing (above) a coarse dendritic structure with a zone (below) of acicular structure. The former apparently consists of dendrites of an Fe-Fe_3C aggregate (gray), surrounded by the Fe-P-C eutectic (clear white) known in artificial irons as steadite (Fe, Fe_3P, Fe_3C), all in a mottled nearly black matrix having the appearance of an iron-graphite eutectic in artificial irons (see Chapter VII). The acicular portion is a form of Fe-Fe_3C Widmanstätten structure. With light etching no structure is shown in the adjacent kamacite below. Picral 30 seconds; × 45.

2. LOCUST GROVE. Part of the dendritic area shown in figure 1. It resembles a structure in a high-phosphorus cast iron. The rounded or elongated gray bodies are the Fe-Fe_3C aggregate referred to above. The perfectly clear matrix surrounding them is steadite. The dark mottled areas are apparently an iron-graphite eutectic. Picral 30 seconds; × 45.

3. LOCUST GROVE. The identical area shown in figure 2 with additional etching 3 minutes with neutral sodium picrate. The clear areas shown in figure 2 are now black, indicating that they are the phosphide eutectic. The gray dendrites are unaffected, indicating that they are an Fe-Fe_3C aggregate. The dark mottled areas are unchanged (black with white flecks), indicating that they are a phosphorus-free aggregate of nickel-iron and graphite.

4. LOCUST GROVE. A portion of the area shown in figures 2 and 3, unetched; × 300. The component that is visible unetched is that of the mottled black areas in figure 2, showing a gray color suggesting the appearance of graphite in artificial iron. The large clear area corresponds with the other components in figure 2—the gray dendrites and the clear phosphide eutectic surrounding them; being wholly metallic these show no structure without etching.

PLATE 66

1. LOCUST GROVE. Part of the acicular border zone shown in plate 65, figure 1, at higher magnification. The structure is due to a precipitation of carbide along crystallographic planes. These planes probably are not octahedral, as the carbide in artificial irons has been found to precipitate along planes with indices of approximately (722). Nital 4 percent, 12 seconds; × 120.

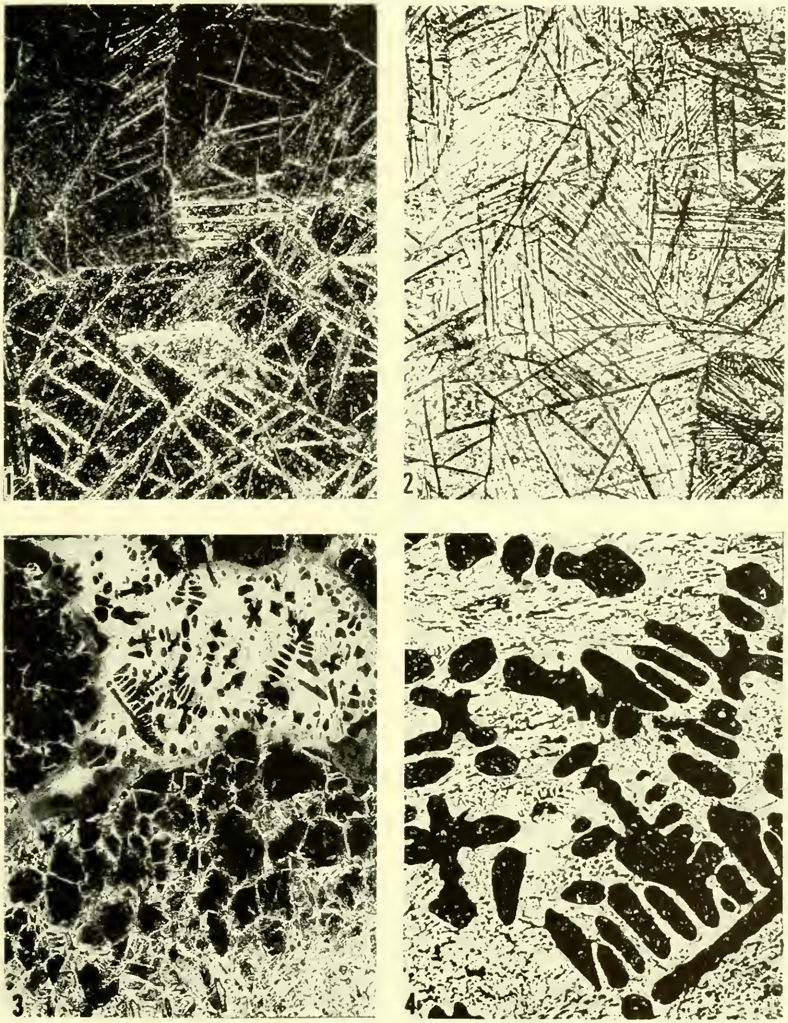
2. LOCUST GROVE. An area similar to that shown in figure 1, with additional etching 3 minutes with alkaline sodium picrate. The picrate darkens the precipitate, showing that it is carbide (cohenite, cementite), a characteristic test for carbide in artifical irons. The structure resembles that of a 3 to 5 percent nickel carburized steel.

The conclusions, both as to this structure and as to the Fe-P-C eutectic structure in the preceding figures, are consistent with the composition of this iron, which contains 0.02 percent of carbon and 0.18 percent of phosphorus. As the inclusion is a spot of carbon enrichment, the percentage of carbon locally might be much higher than the average for the whole mass as reflected in the analysis.

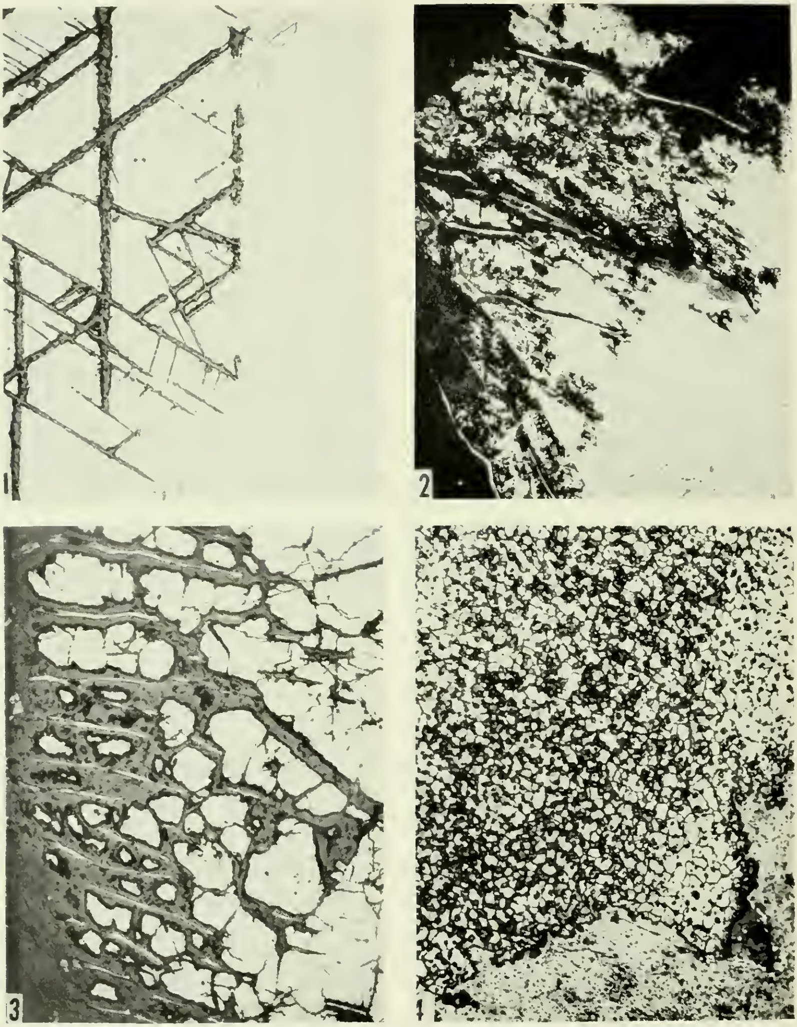
3. CHESTERVILLE, South Carolina; nickel-poor ataxite; Ni-Co 6.25 percent. A spot of carbon enrichment. The upper rounded light area is essentially a white phosphoretic cast iron. The dendrites, probably pearlitic, appear in a white matrix which may be an Fe-Fe_3C eutectic, or perhaps the Fe-C-P eutectic known in artificial irons as steadite. The dark coarsely granular area surrounding it is the equivalent of about a 0.55 percent carbon steel; dark pearlitic grains with white ferrite (kamacite) along their boundaries which increases in proportion outwards. The outermost light granular area (below) is the equivalent of about a 0.25 percent carbon steel in which ferrite predominates; it contains a few small inclusions of phosphide (not steadite).

Of three analyses by Sjöström (in Cohen, 1898) two showed 0.34 phosphorus and two 0.02 percent carbon. One of the three showed no phosphorus, and one no carbon. The variations apparently were due to the presence or absence of cohenite and schreibersite inclusions in the material analyzed. Picral 80 seconds; × 30. U. S. National Museum.

4. CHESTERVILLE. Part of the rounded area shown in figure 3 at higher magnification. Picral 40 seconds; × 150.



Locust Grove and Chesterville Meteorites



Tombigbee River, Seneca Township, Cookville, and Forsyth County Meteorites.

PLATE 67

1. TOMBIGBEE RIVER (Desotoville), Alabama; hexahedrite; Ni-Co 4.78–5.01 percent. Hydroxide invading the mass near the surface along twinning planes indicated by the Neumann lines. The delicacy of the invasion indicates that it is hydroxide and not intrusive melted magnetic oxide. Picral; × 60. U. S. National Museum.

2. SENECA TOWNSHIP, Michigan; finest octahedrite; Ni-Co 11.67 percent. Hydroxide invading octahedral structure. The irregular penetration contrasts with the rounded outlines of areas of intrusive magnetic oxide (pls. 69, 70). Taenite lamellae are not affected. Light picral; × 60.

3. COOKEVILLE, Tennessee; coarsest octahedrite; Ni-Co 6.75 percent. The mass is penetrated by hydroxide, which tends to follow grain boundaries. Taenite lamellae are not affected. Picral 40 seconds; × 60.

4. FORSYTH COUNTY, North Carolina; nickel-poor ataxite; Ni-Co 6.08 percent. Intergranular invasion of hydroxide near the surface. The grains, elsewhere faint, are made conspicuous. Picral 45 seconds; × 45.

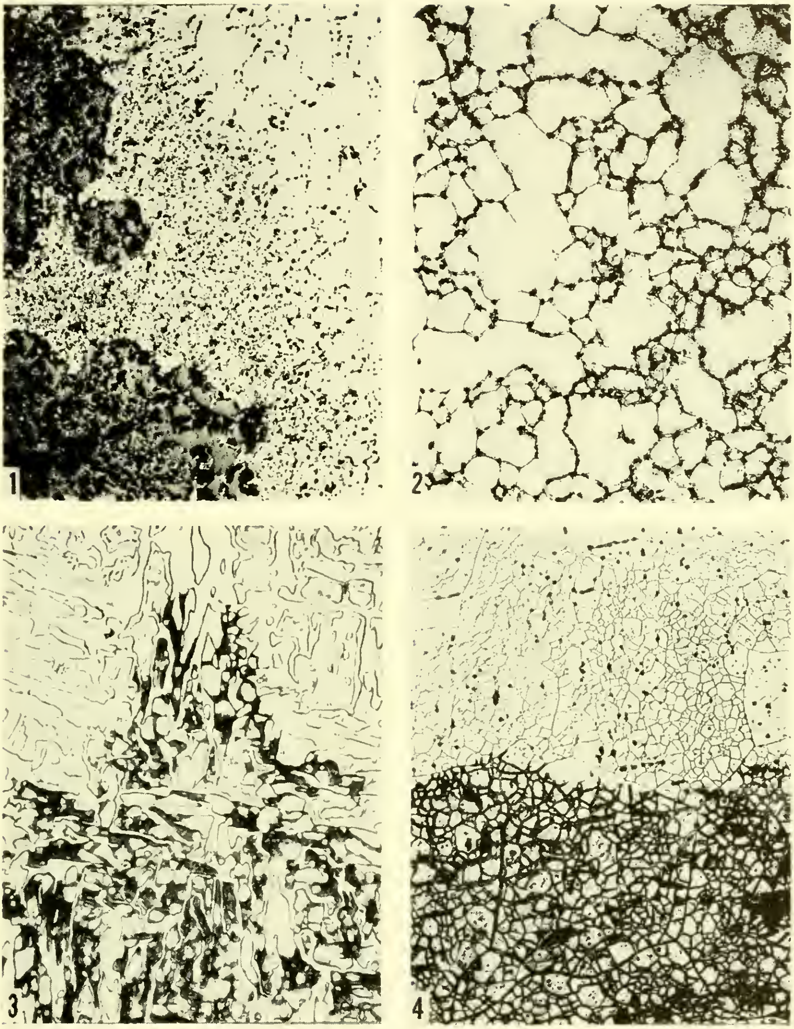
PLATE 68

1. SAN FRANCISCO DEL MEZQUITAL, Mexico; nickel-poor ataxite; Ni-Co 6.33 percent. An area near the surface showing dark masses of invading hydroxide, which also has penetrated somewhat into the iron along grain boundaries. All dark particles are oxide, as no metallic components would be visible without etching. Unetched; × 60. American Museum of Natural History.

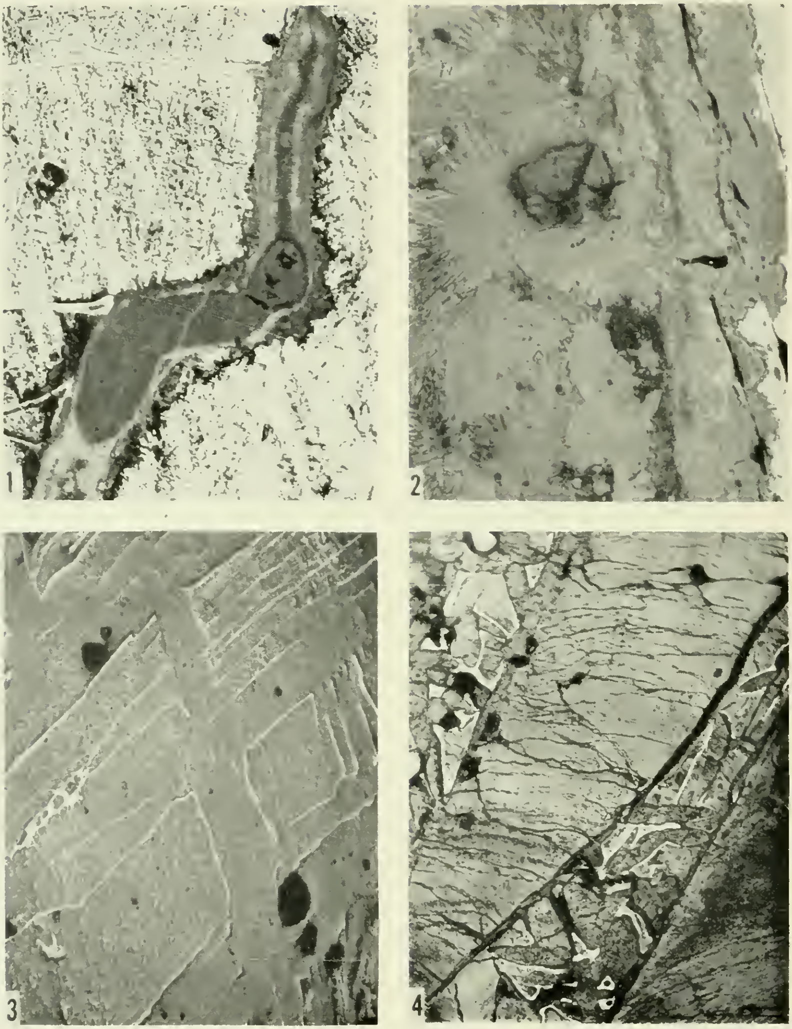
2. SAN FRANCISCO DEL MEZQUITAL. An area of which a portion appears in the upper right part of figure 1. Etching darkens the grain boundaries between the oxide particles, and also reveals a faint secondary granulation (due to reheating) within the larger grains. Picral 40 seconds; × 60.

3. DEEP SPRINGS, North Carolina; nickel-rich ataxite; Ni-Co 14.14 percent. The paraeutectoid structure shown in plate 21 invaded by hydroxide which preferentially affects the kamacite areas. Light picral; × 600.

4. HOLLAND'S STORE, Georgia; granular hexahedrite; Ni-Co 6.35 percent. Intergranular invasion of hydroxide (below) near the surface of the mass. (Compare plate 6.) Picral 75 seconds; × 30.



SAN FRANCISCO DEL MEZQUITAL, DEEP SPRINGS, AND HOLLAND'S STORE METEORITES



SENECA TOWNSHIP, WOOD'S MOUNTAIN, AND SMITH'S MOUNTAIN METEORITES.

PLATE 69

1. SENECA TOWNSHIP, Michigan, finest octahedrite; Ni-Co 11.67 percent. Intrusive magnetic oxide filling a crack in the unaltered interior of the iron. Picral; × 120.

2. SENECA TOWNSHIP. Photograph shows half the width of a crack filled with intrusive oxide, similar to that shown in figure 1. The oxide in cooling developed in places an acicular structure. Picral; × 150.

3. WOOD'S MOUNTAIN, North Carolina; finest octahedrite; Ni-Co 8.61 percent. An area changed wholly to limonite by weathering. The taenite is not oxidized, leaving a remnant Widmanstätten pattern of taenite lamellae and plessite fields. The black spots are surface imperfections. Unetched; × 30.

4. SMITH'S MOUNTAIN, North Carolina; fine octahedrite; Ni-Co 8.52 percent. Oxidized area near the surface. The broad kamacite band has changed wholly to limonite. In the coarse plessite fields on each side the same is true of the kamacite grains, and of the central portions of the grains of dense plessite. These portions being composed of a fine aggregate of kamacite and plessite, and relatively nickel-poor, were susceptible to oxidation. Their high-nickel interfaces, however, resisted oxidation and thus remain as a remnant pattern. Picral 60 seconds; × 60. U. S. National Museum.

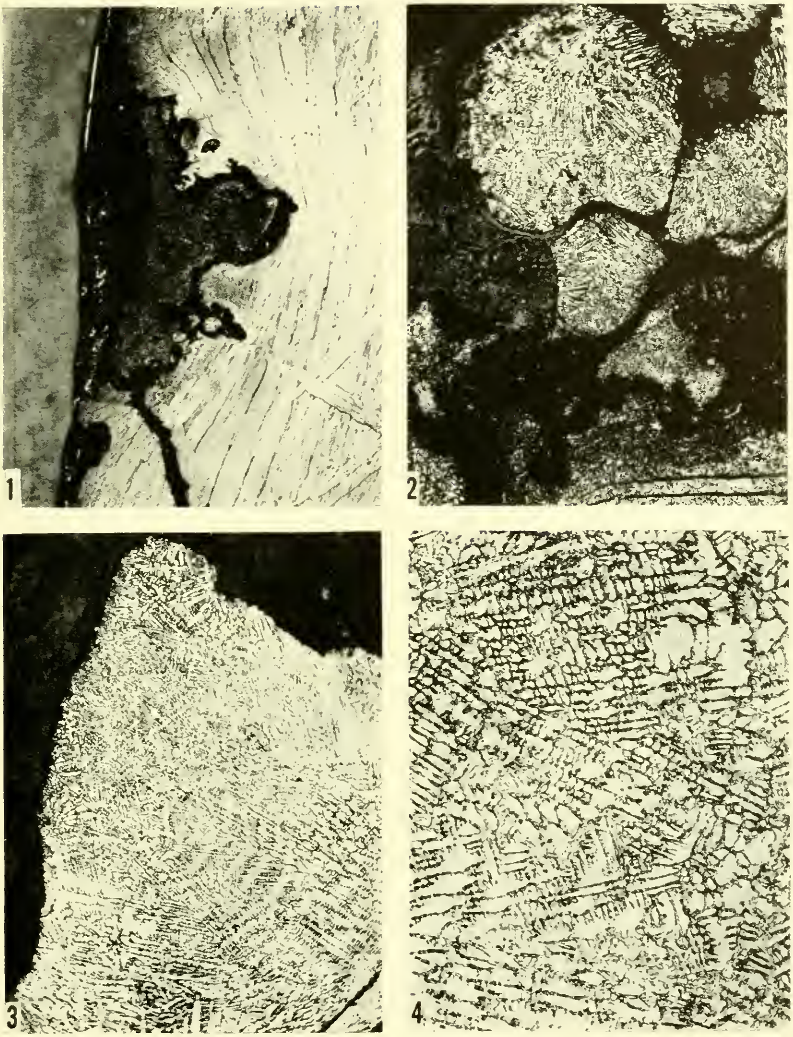
Plate 70

1. Seneca Township, Michigan; finest octahedrite; Ni-Co 11.67 percent. A superficial invasion of intrusive magnetic oxide (with nickel-iron in solution) in the zone of alteration. The dead black areas are oxide; the included area, slightly less dark, consists of nickel-iron rejected during the cooling of the liquid oxide-iron solution. A crack filled with oxide (below) runs some distance into the mass. The curving of the kamacite bands around the oxide area suggests that a troilite nodule existed at that spot, which by reason of its fusibility facilitated the invasion of the molten matter. Light picral; × 9, ordinary light.

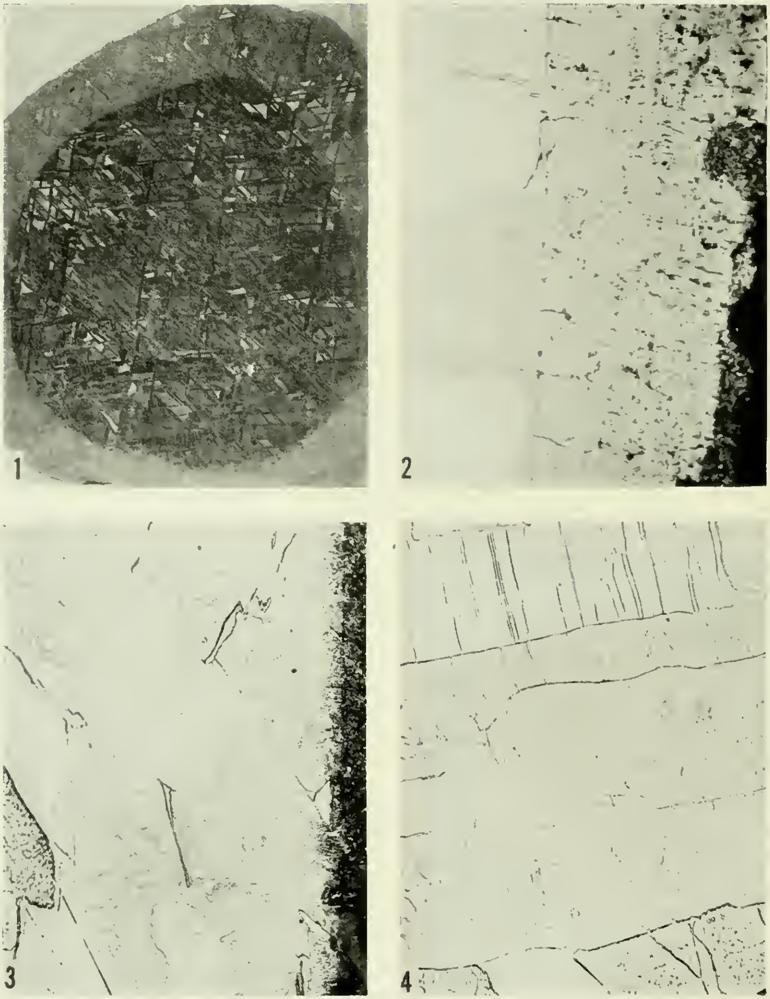
2. Seneca Township. Part of the area shown in figure 1. Droplets of iron rejected in cooling, surrounded by the oxide, have crystallized with a dendritic structure. Light picral; × 60.

3. Seneca Township. A larger area of dendritic crystallization. Light picral; × 60.

4. Seneca Township. Part of the area shown in figure 3 at higher magnification. Light picral; × 150.



Seneca Township Meteorite.



San Francisco Mountains Meteorite.

PLATE 71

1. SAN FRANCISCO MOUNTAINS, Arizona; finest octahedrite. Ni-Co 7.99 percent. The zone of alteration is remarkably distinct. Nital 3 percent 35 seconds; × 1⅕.

2. SAN FRANCISCO MOUNTAINS. Fusion crust (right). The etching is so light that the kamacite shows no structure; field of plessite near left center. Nital 3 percent 15 seconds; × 60.

3. SAN FRANCISCO MOUNTAINS. Kamacite in zone of alteration, showing irregular secondary granulation. Fusion crust at right. Picral 4 minutes; × 60.

4. SAN FRANCISCO MOUNTAINS. An area at the inner boundary of the zone of alteration. The broad kamacite band has been completely altered. In the narrow one above it the alteration is incomplete, a few Neumann lines remaining. The band at the top shows no change. Picral 3 minutes; × 60.

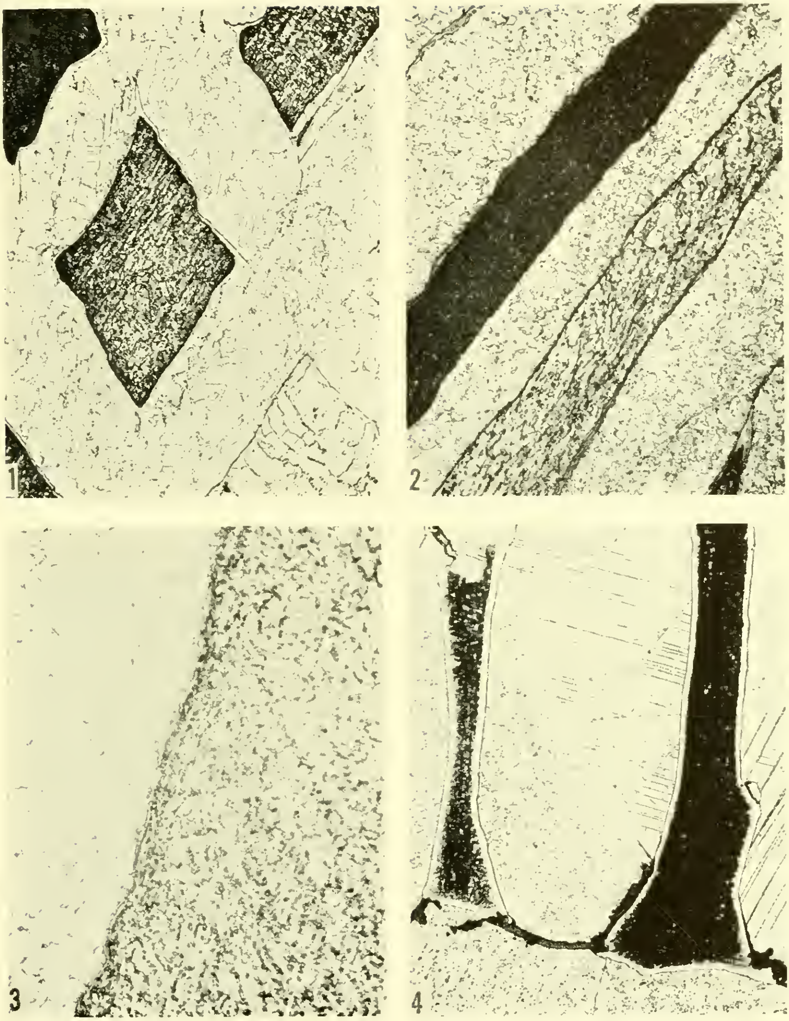
PLATE 72

1. WOOD'S MOUNTAIN, North Carolina; finest octahedrite; Ni-Co 8.61 percent. Normal structure of the iron; the kamacite granulated both in the bands and in the light plessite field (lower right), grains showing Neumann lines. Picral; × 60.

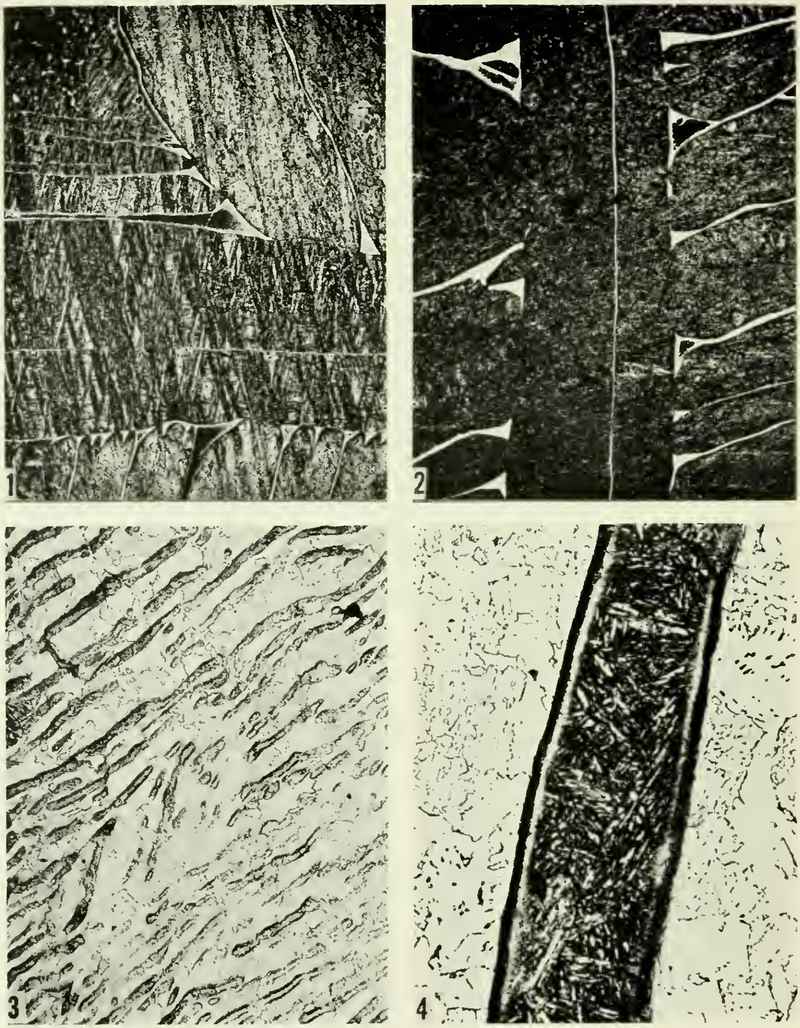
2. WOOD'S MOUNTAIN. An area similar to figure 1 but in the zone of alteration. A fine irregular granulation has replaced the original larger grain structure. Picral; × 60.

3. WOOD'S MOUNTAIN. A dark plessite field, similar to that in the upper left corner of figure 1, in the zone of alteration. The taenite particles are partly diffused. The kamacite (left) shows secondary granulation. Very light picral; × 300.

4. GRANT, New Mexico; medium octrahedrite; Ni-Co 9.98 percent. An area at the inner boundary of the zone of alteration. At the left and below the kamacite is granulated by reheating; above and right, unaltered, with Neumann lines. Two short thick lamellae of taenite with untransformed cores ("spotted" taenite) which with strong etching appear black. Picral 50 seconds; × 30.



WOOD'S MOUNTAIN AND GRANT METEORITES.



SENECA TOWNSHIP AND BURLINGTON METEORITES.

PLATE 73

1. SENECA TOWNSHIP, Michigan; finest octahedrite; Ni-Co 11.67 percent. A kamacite band (horizontal) between fields of very coarse plessite. The kamacite shows a strongly developed gamma-alpha transformation structure, producing a brilliant oriented sheen with macroetching. Picral; × 60.

2. SENECA TOWNSHIP. Part of the same kamacite band shown in figure 1 (here running vertically) but in the zone of alteration. The acicular transformation structure is obliterated in the kamacite, and no definite structure is recognizable.

3. BURLINGTON, New York; medium octahedrite; Ni 8.14 percent (Rockwell, in Silliman, 1844), 8.90 percent (Clarke, 1852). Taenite lamellae of a coarse plessite field much altered and partly diffused by heating. Picral 50 seconds; × 60. Field Museum of Natural History.

4. BURLINGTON. A lamella of dense plessite, altered by heat. In recrystallizing kamacite flakes segregated, appearing as needles in a black unresolved gamma-alpha aggregate. The surrounding kamacite shows a strong secondary granulation. Picral 50 seconds; × 150.

Vogel (1927, fig. 11) gives a photograph of a taenite band in Burlington at lower magnification which he describes as an example of gamma twinning preserved by rapid cooling. No such structure was observed in this specimen, although many lamellae similar to figure 2 bear some resemblance to a twinning structure at lower magnification.

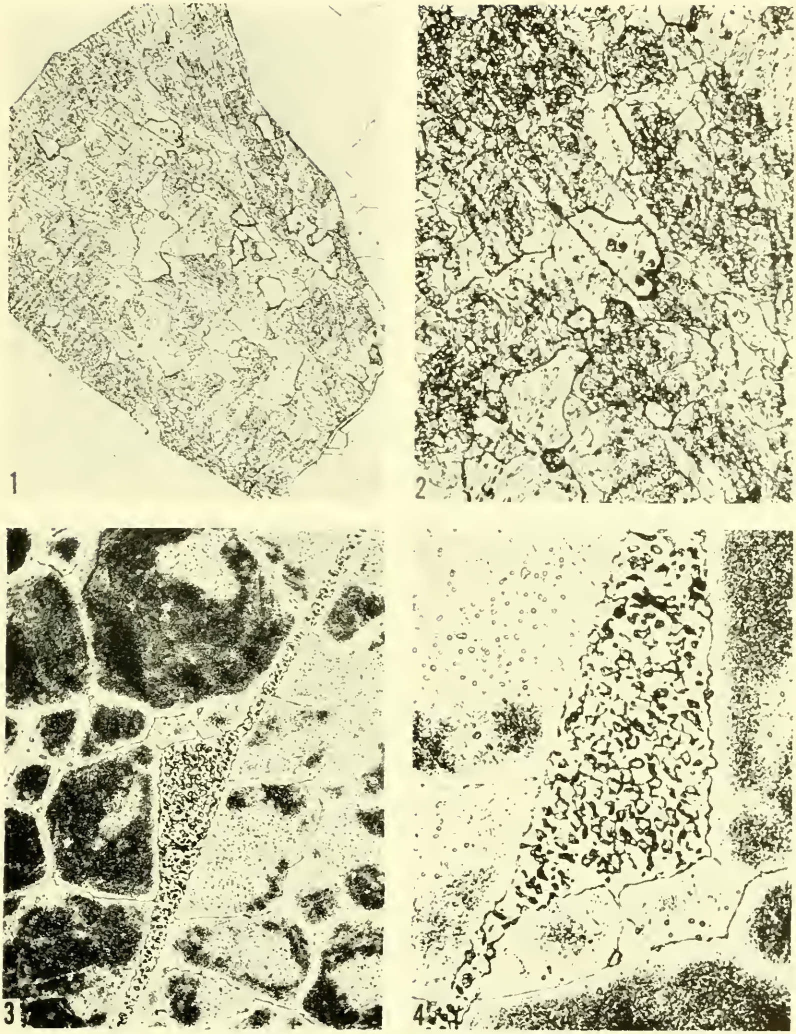
PLATE 74

1. SOCIAL CIRCLE, Georgia; medium octahedrite; Ni-Co 5.40 percent (Everhart in McCallie, 1927). A granular plessite field altered by reheating. Picral 40 seconds; × 60. American Museum of Natural History.

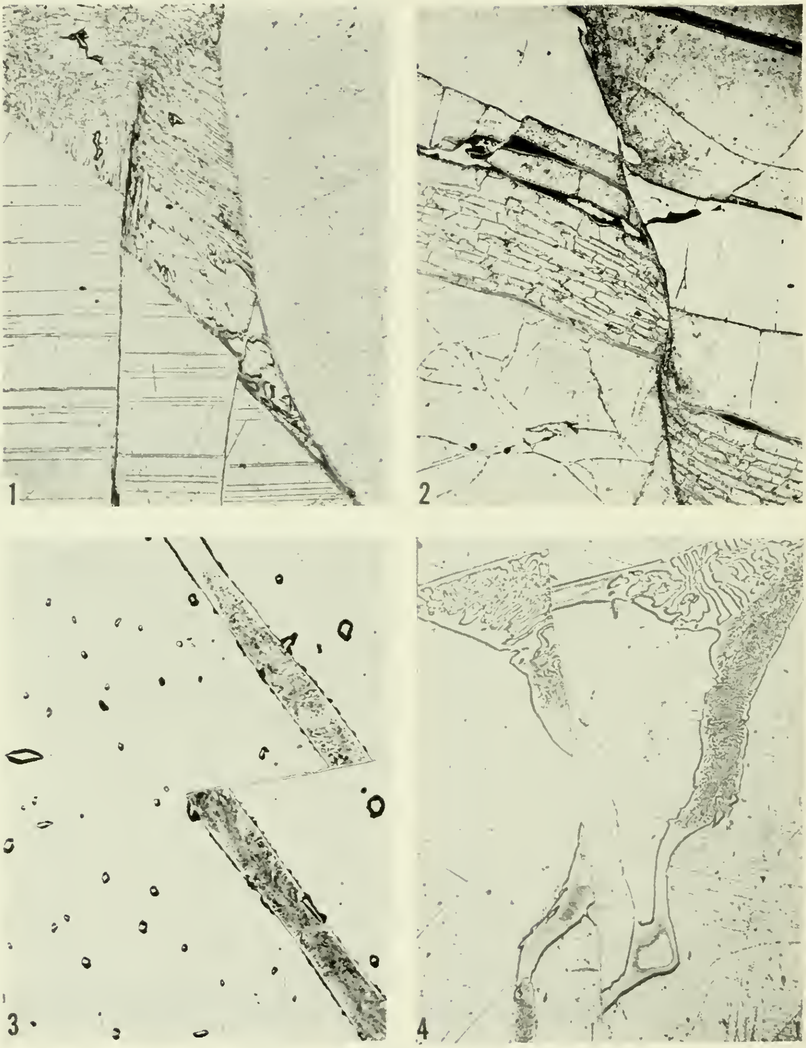
2. SOCIAL CIRCLE. Part of the area shown in figure 1 at higher magnification. The center of this photograph is near the center of the upper half of figure 1. The darker grains probably represent grains of dense plessite in which, after heating, the kamacite segregated in particles in a black unresolved gamma-alpha mixture. Picral 40 seconds; × 150.

3. UNIDENTIFIED. This specimen is from the American Museum of Natural History, whose records afford no indication of its origin. It is a medium octahedrite much altered by cosmic reheating into the gamma-alpha range. This resulted in great alteration of dense plessite, in which the gamma phase began to coalesce; the partial spheroidization of taenite lamellae; and the production of a large amount of black gamma-alpha mixture. The photograph shows (lower left to upper right) an irregular lamella of originally dense plessite between two kamacite bands. The large dark, or mostly dark, kamacite grains constitute the prevailing pattern throughout the mass, with occasional clear or partly clear grains as here shown. In the clear grains the taenite has segregated in minute spheroids and particles; in the dark areas segregation did not take place. Picral 40 seconds; × 60.

4. UNIDENTIFIED. Part of the area shown in figure 3 at higher magnification. The plessite shows rounded particles of taenite and particles of the black gamma-alpha aggregate in a ground of clear kamacite. In the lighter grains the taenite has segregated in spheroidal form. The gamma-alpha aggregate in the dark grains is partly resolved. Picral 40 seconds; × 150.



Social Circle and Unidentified Meteorites.



Canyon Diablo Meteorite.

PLATE 75

1. CANYON DIABLO, Arizona; coarsest octahedrite. Many examples of deformation have been observed in this iron. The figure shows a plessite field with two displacements. Picral 50 percent, nital 50 percent, 12 seconds; × 45.

2. CANYON DIABLO. Displacement running through a body of cohenite and a field of lamellar plessite. Picral 50 percent, nital 50 percent, 12 seconds; × 45.

3. CANYON DIABLO. A displaced lamella of taenite. Owing to the ductility of the taenite, a thin layer connects the separated portions. Picral 50 percent, nital 50 percent, 5 seconds; × 150.

4. CANYON DIABLO. Portions of two different plessite fields. The displacement may have been in two directions with respect to the plane of the section. Picral 50 percent, nital 50 percent, 12 seconds; × 45.

This peculiar plessitic structure was referred to by Vogel as a phosphide eutectic, with illustrations from Canyon Diablo and Toluca (Über die Strukturformen, etc., Abh. Ges. Wiss. Göttingen, math.-phys. Kl., new ser., vol. 12, No. 2, p. 23, figs. 31, 32, 1927). It seems, however, to be clearly a gamma-alpha nickel-iron structure of an imperfect pearlitic pattern, similar to that observed in Otumpa, Leeds, Seeläsgen, Youndegin, and other irons. The graying of the gamma component (taenite) by reason of supersaturation is apparent in this photograph, and still more so at higher magnification, which also shows the alpha component to have a structure similar to that of the surrounding kamacite.

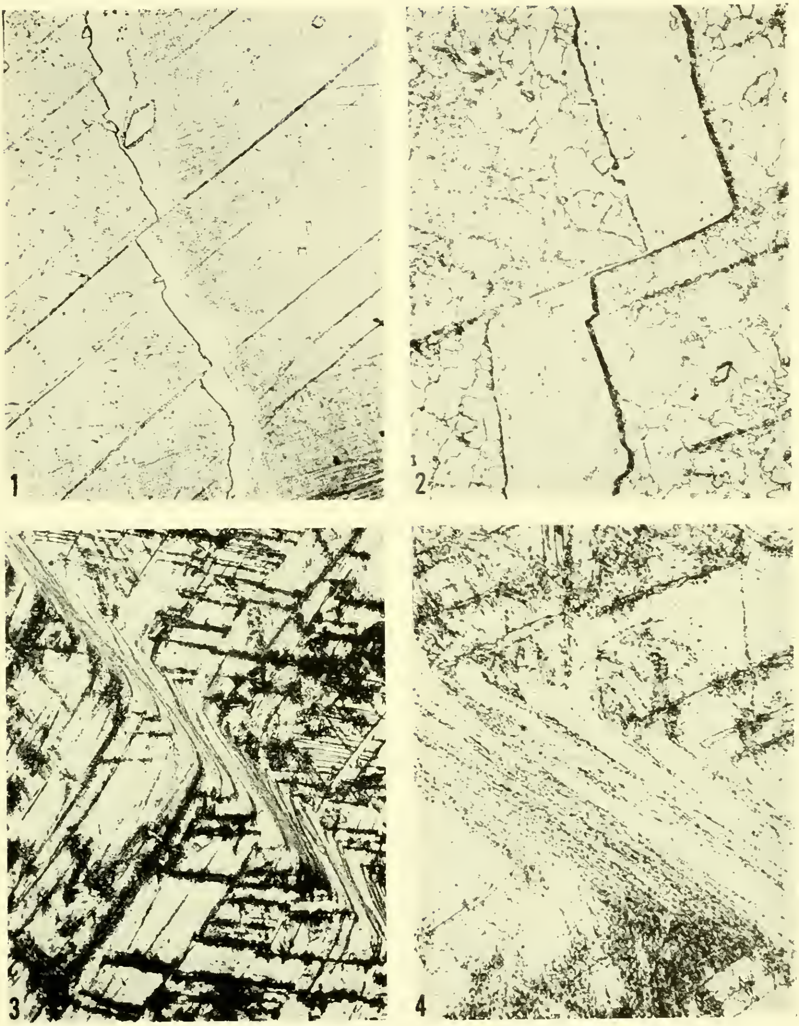
PLATE 76

1. HELT TOWNSHIP, Indiana; coarsest octahedrite; no analysis. A lamella of taenite broken and displaced along the planes of Neumann lines. The meteorite is very small and flakelike in shape, showing throughout incipient alteration by brief heating during atmospheric flight. In this field the alteration was not sufficient to obliterate the Neumann lines, but has formed a zone of granulation along the taenite lamella. A small rhomboidal schreibersite body indents the lamella. Picral; × 60.

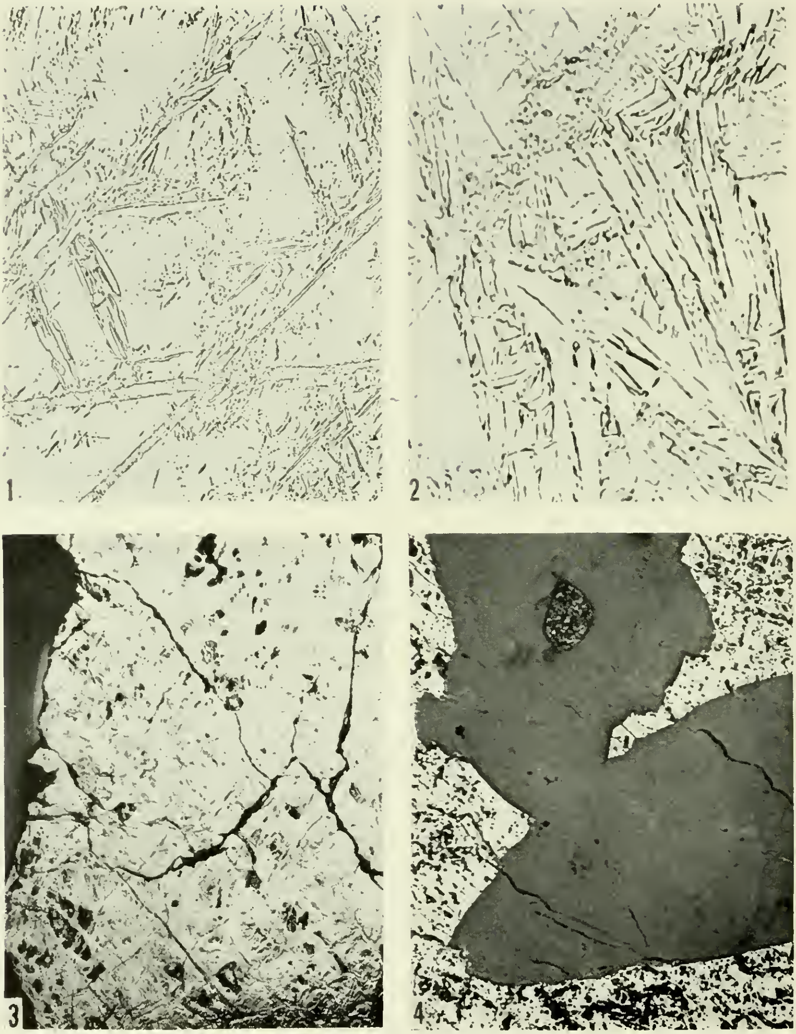
2. HELT TOWNSHIP. Part of the area shown in figure 1 at higher magnification. Owing to the ductility of the taenite, the shearing movement rounded the outside corners slightly and left a thin layer connecting the separated portions of the lamella. The new grain boundaries, evidence of the partial alteration by heat, are in conformity with the displaced structure, showing that deformation occurred before the alteration was accomplished. In the narrow zone of granulation the Neumann lines are partly obliterated. Picral 5 seconds; × 300.

3. NEW BALTIMORE, Pennsylvania; granular hexahedrite; Ni-Co 6.74 percent. The striated band marking a dislocation is about 2 cm. long, lying within one of the very large grains of this iron. It becomes less distinct toward each end, merging into the confused general structure. In many other places this iron bears evidence of more or less distortion, Neumann lines being bent and in places showing the effects of a shearing movement similar to that here shown. Neumann lines are sometimes clear, but mostly are blurred with a black component which in appearance suggests an effect of cold working due to movements within the mass, but which actually is not due to that cause (see pl. 77). Picral 80 seconds; × 30.

4. NEW BALTIMORE. Part of the area shown in figure 3 at higher magnification. Picral 30 seconds; × 150.



HELT TOWNSHIP AND NEW BALTIMORE METEORITES.



New Baltimore, Salina, and Grant Meteorites.

PLATE 77

1. NEW BALTIMORE (see pl. 76). Typical structure at high magnification. The peculiar appearance, suggesting cold working at lower magnification, is shown to be a gamma-alpha transformation structure. Picral 90 percent, nital 10 percent, 15 seconds; × 600.

2. NEW BALTIMORE. An area similar to the last, × 1,200. The nature of the structure is more apparent. Although the presence of such a structure might seem anomalous in an iron with only 6.74 percent Ni-Co, which should be almost wholly in the alpha phase, still analogous structures are found in irons with still lower content—e. g.. Primitiva (pl. 10) with 5.61 percent Ni-Co, and San Francisco del Mezquital (pl. 78) with a Ni-Co content of 6.33 percent. The apparent explanation is that the fine gamma-alpha structure was a result of rapid cooling, analogous in its manner of formation to martensitic structures in artificial irons.

3. SALINA, Utah; medium octahedrite; no analysis. This iron has been changed to limonite by weathering. Traces of the original octahedral pattern are discernible. Unetched; × 1½, central illumination.

4. GRANT, New Mexico; medium octahedrite; Ni-Co 9.98 percent. A silicate inclusion in troilite. The surface of the latter was chipped in polishing. Picral 60 seconds; × 30.

Plate 78

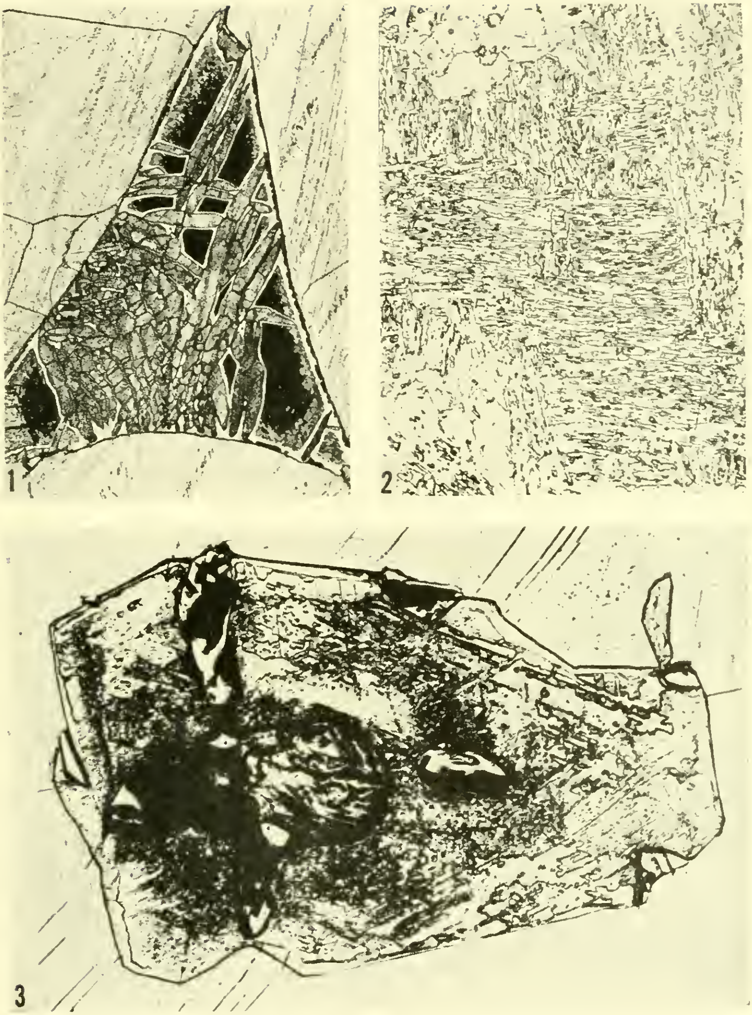
1. Trenton, Wisconsin; medium octahedrite; Ni-Co 7.73 percent (1869). A coarse plessite field in which kamacite lamellae are darkened by the presence of a fine gamma-alpha aggregate, a result of incomplete transformation, an example of the so-called "spotted" kamacite. In this iron the kamacite generally shows an acicular gamma-alpha structure reflecting incomplete transformation; see plate 35. Picral 50 seconds; × 60.

2. San Francisco del Mezquital, Mexico; nickel-poor ataxite; Ni-Co 6.33 percent. Though having a nickel-cobalt content typical of hexahedrites, and in the alpha phase, this iron in places shows an acicular gamma-alpha transformation structure similar to that in a number of octahedrites (pl. 35). Compare the similar structure in New Baltimore (Ni-Co 6.74 percent) and Primitiva (Ni-Co 5.61 percent) in which this structure also occurs (pls. 76, 77, 10). Picral 40 seconds; × 150.

3. Sierra Gorda, Chile; hexahedrite; Ni-Co 5.83 percent (Henderson, 1941). An atypical plessite field. Although this iron is a "normal" hexahedrite, with a Ni-Co content below the average even for that group, it contains a number of minute areas suggesting plessitic structure of which this was the only one of definite character. It shows irregular lamellae of taenite and a considerable amount of black gamma-alpha mixture. Although the structure is irregular and confused, it shows fairly distinct orientation, both as to the lamellae and, in places, the dark gamma-alpha aggregate. The dead black spots were occupied by large schreibersite inclusions which were chipping out in polishing, only remnants remaining. Three small schreibersite bodies also appear in the edges of the field.

The field is mostly surrounded by a border of taenite, which is not darkened by reason of supersaturation, although the etching was very strong. Light etching did not reveal the structure at all. Such a structure would seem to be a product of incipient transformation at a relatively high temperature, followed by rapid cooling; thus some taenite of low nickel content formed in a high range, and which normally would have disappeared, was preserved because the mass so quickly became rigid. In such a case there would be a relatively small difference in the nickel content of the taenite and of the kamacite, and therefore little difference in their solubility in acid, which would explain the fact that the structure was not visible with light or even moderate etching.

While the presence of taenite in a typical hexahedrite is unusual, it is found also in Otumpa (pl. 44), which has a Ni-Co content even lower than Sierra Gorda. Picral 200 seconds; × 60.



Trenton, San Francisco del Mezquital, and Sierra Gorda Meteorites.

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[3] Hexahedrite.

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[2] Ataxite, nickel-rich.
[3] Hexahedrite.
[4] Ataxite, nickel-poor.

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    Braunau, Cedartown, Central Missouri, Coahuila, Desotoville, Fort Duncan, Hex River Mountains, Holland's Store, Horse Creek, Indian Valley, Kendall County, New Baltimore, Otumpa, Rio Loa, Sanchez Estate, Sandia Mountains, Scottsville, Sierra Gorda, Tombigbee River, Walker County—*q. v.*]
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[2] Ataxite, nickel-rich.
[3] Hexahedrite.
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[2] Ataxite, nickel-rich.
[3] Hexahedrite.
[4] Ataxite, nickel-poor.

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[1] Octahedrite.
[2] Ataxite, nickel-rich.
[3] Hexahedrite.
[4] Ataxite, nickel-poor.

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[1] Octahedrite.
[2] Ataxite, nickel-rich.
[3] Hexahedrite.
[4] Ataxite, nickel-poor.

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[2] Ataxite, nickel-rich.
[3] Hexahedrite.
[4] Ataxite, nickel-poor.

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[1] Octahedrite.
[2] Ataxite, nickel-rich.
[3] Hexahedrite.
[4] Ataxite, nickel-poor.

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